Open Carboniferous Limestone pavement grike microclimates in Great Britain and Ireland: understanding the present to inform the future

Thesis submitted in accordance with the requirements of the University of Chester for the degree of Doctor of Philosophy

By

Peter James York

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Abstract

Limestone pavements are a distinctive and irreplaceable geodiversity feature, in which are found crevices known as grikes. These grikes provide a distinct microclimate conferring a more stable temperature, higher relative humidity, lower light intensity and lower air speed than can be found in the regional climate. This stability of microclimate has resulted in an equally distinctive community of flora and fauna, adapted to a forest floor but found in an often otherwise barren landscape. This thesis documents the long-term study of the properties of the limestone pavement grike in order to identify the extent to which the microclimate may sustain its distinctive biodiversity, to provide recommendations for future research which may lead to more effective management. Over a five-year study, recordings of temperature, relative humidity, light intensity and samples of invertebrate biodiversity were collected from five limestone pavements situated in the Yorkshire Dales and Cumbria in Great Britain, and The Burren in the Republic of Ireland. An extensive description of the grike microclimate was undertaken using the data collected to understand the extent of the microclimate stability of the grike and the conditions for variation in the grike microclimate. Further insights into the grike microclimate were gained through simulation techniques more commonly used in engineering, to explore the effects of air flowing over a grike, the light from the sun entering the grike and regression analysis to simulate the temperature within the grike in the present and projected for the future.

This study has indicated that although the whole of the grike confers a degree of microclimatic stability, it is made up of a less stable upper zone and a more stable lower zone. The instability of the upper zone is hypothesised to result from the extent to which the majority of light and external air can enter the grike, whereas the stability of the lower zone may be governed by the thermal stability of the limestone surrounding it. Based on this zonation and the projections for the grike temperature, it is hypothesised that climate change will have the most substantial effects in the upper grike zone where species obligated to this area could be most heavily impacted. This study recommends a range of areas in which research may be employed so that the limestone pavement habitat may be successfully managed in Great Britain and the Republic of Ireland.

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List of abbreviations

AIC = Akaike Information Criterion
ANOB = Area of Outstanding Natural Beauty
ANOVA = Analysis of variance
BAP = Biodiversity Action Plan
CFD = Computational Fluid Dynamics
CMIP = Coupled Model Intercomparison Project
DEFRA = The Department for Environment, Food and Rural Affairs
EC = European Council
EEC = European Economic Community
EPA = Environmental Protection Agency
EU = European Union
EW = East West
GPS = Global Positioning System
ICUN = International Union for Conservation of Nature
IPCC = Intergovernmental Panel on Climate Change
JNCC = Joint Nature Conservation Committee
LGM = Last Glacial Maximum
LPO = Limestone Pavement Orders
NBN = National Biodiversity Network
NE = Northeast Southwest
NS = North South
NW = Northwest Southeast
NWF = National Wildlife Federation
OS = Ordnance Survey
OSi = Ordnance Survey Ireland
PCA = Principal Component Analysis
PRP = Percentage Relative Precision
RCP = Representative Concentration Pathway
RIGS = Regionally Important Geodiversity Sites
SAC = Special Area of Conservation
SEA = Strategic Environmental Assessment
SSSI = Site of Special Scientific Interest
UNESCO = United Nations Educational, Scientific and Cultural Organization
UK = United Kingdom
UKCIP = United Kingdom Climate Impacts Programme
URL = Uniform Resource Locator
UKCP = United Kingdom Climate Projections
UKCP18 = United Kingdom Climate Projections 2018
W/H = Width to height ratio

Declaration

"The material being presented for examination is my own work and has not been submitted for an award of this or another HEI except in minor particulars which are explicitly noted in the body of the thesis. Where research pertaining to the thesis was undertaken collaboratively, the nature and extent of my individual contribution has been made explicit."

Signed ………………………………………………………. Date ………………………

"The way to deal with an impossible task was to chop it down into a number of merely very difficult tasks, and break each one of them into a group of horribly hard tasks, and each of them into tricky jobs, and each of them..."
— Terry Pratchett, Truckers

"The true scientific mind is not to be tied down by its own conditions of time and space. It builds itself an observatory erected upon the border line of present, which separates the infinite past from the infinite future. From this sure post it makes its sallies even to the beginning and to the end of all things"
— Arthur Conan Doyle, **The Poison Belt**

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1. Introduction and aims

1.1 Limestone pavements

Limestone pavements are distinctive, naturally formed landscape features consisting of exposed limestone, crisscrossed with fissures and platforms (grikes and clints). The grikes afford opportunities for unusual microclimates which are a refuge for a distinctive community of species within a subterranean habitat. Due to a lack of long-term study, the foundations of this microclimate are undefined, and the impacts of future climatic changes are unknown. Providing the direction for the research required for a successful grike management strategy is the focus of this study.

Figure 1.1 Fanore limestone pavement (The Burren, Republic of Ireland).

1.1.1 Limestone Pavement formation and grike features

The action of advancing ice sheets began the formation of limestone pavements by scouring the surface of the limestone and stripping the surface material to expose the horizontally bedded limestone (Williams, 1966). As the ice receded, the bare flat sheets of limestone were covered by till, reburying the pavements (Webb & Glading, 1998). Under these conditions, the grikes began as faults produced by movement along weaknesses in the rock. The acid present in rainwater percolated through the soil acting on the faults by widening them. Over time, the soil covering a pavement eroded to expose grikes as fissures, leaving soil remnants within the grikes (Vincent, 1995). The karstic (water-worn limestone) features of grikes and clints normally form on massive bedding planes with jointing as a result of structural deformation (Vincent, 1995).

The features of the limestone pavement are the clints, grikes and runnels. Clints are the blocks of limestone that constitute the paving, and runnels are the drain-like channels eroded into the surface of the clint (Jain, 2014). Grikes are the main feature of this thesis, and the definitions of this feature are explored as part of the literature review. In this study, the definition of a grike combines multiple definitions as follows "*A vertical fissure, formed by the solutional widening of joints, which regularly divide an exposed limestone surface into sections or clints".* This definition combines the existing definitions of a grike collected by Burek and York (2011), Sweeting et al. (1965), Ward and Evans (1975), Goldie and Cox (2000), and Gray (2013). Most grikes are orientated in the cardinal compass directions (Jennings, 1985). Grikes have been observed to reach over 2m in both width and depth, but most are much narrower and shallower falling within a mean of 0.6m deep and 0.3m wide (Willis, 2011).

1.1.2 Underlying geology and Distribution

The limestone that makes up the pavements of Britain and Ireland is a sedimentary rock in which calcium carbonate is the main constituent (Goudie, 1994). This limestone is present throughout the United Kingdom and the Republic of Ireland, and represents geological periods from the Cambrian through to the cretaceous (Williams, 1966; Waltham, Simms, Farrant & Goldie, 1997). In the UK, limestone is predominantly from the Carboniferous period; however, the much older Cambrian or Ordovician limestone of the Durness Group is found in parts of Scotland (Vincent, 1995; Waltham, Simms, Farrant & Goldie, 1997). All countries in the British Isles contain limestone pavements; they are also found in a small number of other countries around Europe (European Environment Agency, 2013). The sites used in this study are situated in Yorkshire, Cumbria, and The Burren. Although each site is a limestone pavement, the underlying geology of the location provides a distinctive character which is further explored in the literature review of this subject.

1.1.3 Limestone pavement and geodiversity

Gray (2013) defines geodiversity as "the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landform, topography, physical processes) and soil and hydrological features. It includes their assemblages, structures, systems and contribution to landscapes". Further definitions place importance on geodiversity as the "framework for life on earth" (Stanley, 2001) and state that "biodiversity is a part of geodiversity" (Stanley, 2002). Within the context of limestone pavements, geodiversity includes the underlying limestone of the site, the lithology of that limestone, the structure of the limestone pavement brought about by glacial and weathering processes and the soils found on and within the pavement. The definition of geodiversity is still evolving to include new aspects of geology (Gray, 2013). As part of this thesis, the argument will be made that the geodiversity of a limestone pavement's structures not only apply to the diversity between pavements but within a limestone pavement. This argument will be based on the link between biodiversity and geodiversity (Stanley, 2001; 2002).

1.1.4 Grike Microclimate

Microclimates are commonly defined as the collection of climatic conditions measured near or within a specified small localised area (Geiger, Aron & Todhunter, 2009). Changes to microclimates are reported to result from multiple factors originating in the macroclimate and surrounding area (Stoutjesdijk & Barkman, 2014; Jones, 2013). The grike microclimate is characterised as containing a more stable temperature and higher relative humidity as the distance from the surface increases (Heslop-Harrison, 1960, Dickinson; Pearson & Webb, 1964). It is hypothesised that the variation in microclimate is linked to the amount of light radiating to different areas of the grike, impacting the microclimate at different depths and in different orientations of grike (Dickinson, Pearson & Webb, 1964; Alexander, Burek & Gibbs, 2007). Several prior authors have undertaken studies of grike microclimates; despite these efforts, there are still gaps in knowledge concerning the nature of the grike microclimate, discussed in Subsection 1.2.

1.1.5 Grike flora and fauna

Ward and Evans (1976) identified that limestone pavements hold a characteristic community of floral species due to the structures provided by grikes, clints and runnels. Many of the species present are more commonly found in wooded habitats, and some pavements contain communities which bear little resemblance to the surrounding vegetation (Ivimey-Cook, 1965; Webb, 1961). A link has been recognised between the microclimate and the floral species found within grikes (Dickinson, Pearson and Webb, 1964; Silvertown, 1983). Several floral species found within limestone pavements are recognised as rare or nationally scarce (Gilbert, 1970; Usher, 1980; Wardlaw & Leonard, 2002). Faunal species within the grike have not received as much attention as flora however despite this several species lists exist (Platts, 1977; Killeen, 1997; Lloyd-Jones, 2001) and among these species are two BAP priorities (Natural England, 2013, Killeen, 1997). Invertebrate species have been found to rely on some of the notable grike flora and the structure of the grike (Coleburn, 1974; Butterfly Conservation, 2016). No research known to the author, has been conducted to identify a direct relationship between invertebrates and grike microclimate; however, pavement character and grike orientation have been shown to affect species distribution (Sheehy, 2004; Swindale, 2005; Willis, 2011)

1.1.6 Limestone pavement conservation status and management

In general terms, the conservation status of limestone pavements in Britain and Ireland is currently considered to range from “Unfavourable/Inadequate” in the Republic of Ireland to “Unfavourable/ Bad” in Great Britain (European Environment Agency, 2013). These designations do not, however, account for the variety of sites found and their various levels of conservation which have been detailed by other authors (Murphy & Fernandez, 2009; Joint Nature Conservation Committee, 2013; Rodgers, 2013). The protection for limestone pavements varies by country, ranging from specific protection by criminal law in England to more general protected site designations in the rest of Britain and Ireland (National Parks & Wildlife Service, 2019; Joint Nature Conservation Committee, 2019). Management of limestone pavements has mainly focused on the immediate threats of overgrazing, scrub management, disturbance and sustainable tourism (Pendry & Allen, 1999; Natural England. 2001; Dunford, 2002; Milligan, 2003; Burren and Cliffs of Moher: GeoPark, 2017). Recently some areas containing limestone pavements are proposing management plans which account for climate change; however, these do not focus on the role of limestone pavements specifically (Yorkshire Dales National Park Authority, 2011; Arnside & Silverdale Partnership, 2015; Cooney & Gaffrey, 2015).

1.1.7 Climate change, uncertainty and refugia

Climate change is described as a large-scale and long-term shift in the planet's weather patterns and average temperatures (Pachauri et al., 2014). Unless otherwise stated, climate change in the context of this thesis refers to anthropogenic climate change. These are the future projected changes to the global climate. The “dominant cause” of this change is “extremely likely” to be the increased concentration in atmospheric greenhouse gases produced by human actions (Pachauri et al., 2014). These greenhouse gasses affect the climate of the planet by trapping a portion of the solar heat radiation emitted by the Earth, resulting in a warming climate (Murphy, 2018). Throughout the globe and in Britain and Ireland, there are varied effects of climate change dependent upon the location and the emissions scenario being explored (Pachauri et al., 2014). The generalised effects of climate change are projected to be higher mean annual temperatures, changing rainfall and rises in sea level. The projections made, however, contain uncertainties stemming from the socio-economic scenarios used and imperfections in the knowledge and models (McMahon, Stauffacher & Knutti, 2015). The changes to the climate are predicted to produce further changes to natural systems (Murphy, 2018). The impacts of climate change on the natural environment vary by region, habitat, the organism being affected and multitudinous exacerbating factors creating a great deal of uncertainty in predicting the effects on the natural world (Thomas et al., 2011; Thuiller et al., 2019). Impacts can both positively and negatively affect abundance, distribution, lifecycle and behaviour of organisms (Natural England, 2015). The spatial scale over which climate is predicted often does not match the scale on which species operate (Hannah et al., 2014). This discrepancy can mean that refugia, or areas where the impacts of climate change are reduced are not identified by climate projection models.

Originally a term used to describe an area in which organisms were protected from past climatic change (Hewitt, 2000) the term refugia has now entered a more recent usage as a habitat which will protect from future disturbances like those predicted to occur (Keppel et al., 2012). Microclimatic stability and habitat variation are cited as a key component of a potential refugium (Rull, 2009). This thesis details the investigations to explore the possibility that grikes may be suited to provide microrefugia during future anthropogenic climate change.

1.2 Current gaps in knowledge

1.2.1 Microclimate

1.2.1.1 Long term study

As yet no study of grike microclimate known to the author has produced a data set of over a year. Shorter studies of grike microclimate undertaken for under a month have identified that inner grike relative humidity is high, light is low, and the temperature is relatively stable (Dickinson, Pearson & Webb, 1964). Studies spanning multiple months identified that grike orientation and season influence microclimate (Burek & Legg, 1999; Alexander, Burek & Gibbs, 2007). One reason for the lack of long-term study is a large number of hazards to data collection on limestone pavements. Attempts made to collect long term microclimate data have been hindered by animal and human interference compounded by the isolation of sites (Foster. S, personal communication, September 2010). These drawbacks have led to data corruption and equipment faults going undiscovered.

Studies undertaken for extended durations of a year or longer would be likely to uncover any seasonality to the microclimate and identify whether these trends interacted with other variables such as orientation. Similar long-term investigations of caves found the season and other animal interaction such as human exhalation and movement influenced the microclimate within the body of the cave (Hoyos et al., 1998; Bucher, 1999). Similarly, longer study duration and focus on the microclimate in all seasons will also make it possible to present hypotheses to explain the physical processes which produce the stability of the grike microclimate.

The increased occurrence and impacts of severe weather events are emerging as one of the key impacts on ecosystems (Jentsch, 2007). The impacts of drought on the grike microclimate were recorded by Heslop-Harrison (1960); however, a longer period of study will allow the time needed to observe other instances of severe weather impacting the microclimate of the grike. The impacts of severe heat, cold drought and precipitation have not yet been observed in a grike, nor have they been compared to normal conditions.


Figure 1.2 Eyarth Rocks limestone pavement under severely cold conditions (North Wales, UK).

By providing a greater degree of insight into the internal and external factors influencing the grike microclimate formation, it will be possible to provide the basis for a preliminary modelling exercise to quantifiably build an informative simulation of the temperature of a grike for a specific emissions scenario. A similar amount of long-term study has allowed a greater understanding of the factors which influence the cave microclimate (Wigley & Brown, 1971). This has allowed the cave microclimate to be modelled and later measured to account for anthropogenic climate change (Wigley & Brown, 1976; Domínguez-Villar, Lojen, Krklec, Baker & Fairchild, 2015). Such an understanding of cave microclimate stability in conjunction with fossil records has brought some to the conclusion that caves have acted as refugia in periods of past climatic change (Stewart & Lister, 2001). Through the longer-term study of the grike microclimate, similar arguments may be presented to propose the grike to be a possible microrefugium.

1.2.1.2 Air movement in a grike

A study of web building by the European garden spider (*Araneus diadematus*) in grikes at Scar Close limestone pavement showed that webs in narrower grikes were confined to one grike wall whereas wider grikes contained webs which spanned the entire grike (Colebourn, 1974). The behaviour observed was hypothesised to be because air currents in wider grikes allowed for threads to be carried across the grike whereas narrow grikes were sheltered from air currents and therefore contained fewer or weaker air currents. Further study of deeper grikes in Canada presents the theory that airflow in grikes becomes weaker as depth increases, which influences the microclimate of the grike (Yarranton, 1969). The influence of the grike on air passage remains hypothetical; however, there is research from other fields to suggest that structures similar in shape to grikes named street canyons can alter the movement of air entering an aperture and influence a microclimate within. Street canyons are the gaps between large rows of buildings such as New York's 5th Avenue. In such structures, the ratio of canyon height to width influences the strength of turbulence toward the tops of buildings (Murena, Favale, Vardoulakis & Solazzo, 2009) as was hypothesised by Colebourn (1974) in the case of grikes. Although similar in shape, street canyons do not replicate the grike exactly. Street canyons are considerably larger and influenced by traffic and other anthropogenic effects (Wedding, Lombardi & Cermak, 1977; Murena, Favale, Vardoulakis & Solazzo, 2009). A study is yet to simulate airflow within a grike and test the hypothesised influence on the microclimate (Colebourn, 1974; Yarranton & Beasleigh, 1969).

1.2.1.3 Grike potential as a microrefugia

It is understood that some habitats may retain more unchanged biodiversity during climate change (Suggitt, 2014), due to several factors relating to microclimate (Stevenson, 1985). These areas have been dubbed refugia (plural) and refugium (singular), the term 'refugia' is sometimes used without distinguishing between macro- and microrefugia. The two categories fall on a sliding scale; however, microrefugia may be distinguished by requiring finer scale understanding of local climate than are found in commonly used climate grids (Ashcroft, 2010). The minimum viable size of a microrefugia is dependant on the habitat size required to support the population within it (Ashcroft, 2010). This relatively new area of research is one to which limestone pavement grike habitats may be exceptionally well suited.

The stability of the grike microclimate and variation in the grike habitat has led limestone pavements to be described as a microrefugium for flora in open situations (Ward & Evans, 1976). These same attributes provide an argument for the limestone pavement grike to be considered as potential a microrefugium for species to inhabit during the projected future climate change. Grikes may have provided this function during past changes in climate as some grikes still provide sanctuary for some relict woodland plant species from the Late Devensian and early Holocene (Ingrouille, 2012). It is considered particularly difficult to identify habitats which will become refugia in the future (Rull, 2009). There are still several unanswered questions relating to the long-term stability of the grike microclimate that require answers in order to inform the refugia debate.

1.2.2 Fauna

1.2.2.1 There is little understanding of the invertebrate life found in deeper grikes

Most of the studies conducted to investigate the invertebrate life of limestone pavements have involved visual surveying of the limestone pavement clints, grike and surrounding grassland (Colebourn, 1974; Nichols, 2009; Willis, 2011; Fröberg et al., 2011). Some studies used pitfall traps situated within the grikes; however, due to limitations of this method, traps could only be sited in shallower grikes (York, 2009). There has yet to be a documented English language investigation to study the invertebrate life found at the bottom of some the deeper grikes measuring over one metre. Due to this lack or research little is known about what lives there.

1.2.2.2 Little is known about the link between grike depth, and the invertebrate life found there

The studies which have been conducted to identify species of invertebrate within grikes have largely focused on the effect of pavement type, grike orientation, grike position and season on the prevalence of different invertebrates (Lloyd-Jones, 2001; Sheehy, 2004; Swindale, 2005; York, 2009; Willis, 2011). While these studies have the potential to provide valuable information, and some have linked the mean grike depth of each pavement to the distribution of species (Willis, 2011). They are unpublished, and there are aspects of the methodology which prevent direct comparisons between microclimate and invertebrate populations. None of the previous studies has used sampling techniques capable of sampling grike invertebrates from deeper grikes, thus limiting the range of microclimates available to a survey. These previous surveys also often do not directly link the sample to the grike. No study of invertebrates known to the author has emulated Silvertown's (1982) study of grike flora and conducted a coordinated survey of both biodiversity and microclimate in the same pavement allowing for unambiguous comparisons between biodiversity, depth and microclimate.

1.2.3 Call to action

Renowned for their beauty and the rarity of the species associated with them, limestone pavements in Great Britain and the Republic of Ireland are an important habitat that requires considerably more research to be fully understood, effectively conserved and managed, within the context of a rapidly changing climate. The nationally important flora and fauna reliant upon this exceptional geodiversity feature owe much of their survival to the highly specialised microclimate found within grikes in the pavement (Ward & Evans, 1976). This study intends to provide the initial research and simulations required in order to better understand the grike microclimate, the importance of microclimate to invertebrates, and how this may change. It is intended that this study will lay the groundwork and identify future areas of research which may lead to effective management guidance.

1.3 Aims and objectives

1.3.1 Aims of the thesis

The broad aims of this project are to:

1. Provide a detailed description of the microclimate found within the grikes on open carboniferous limestone pavements in Great Britain and Ireland
2. Identify the research which is needed in order to provide more effective guidance for the management of open carboniferous limestone pavements in Great Britain and Ireland with regard to climate change.

1.3.2 Objectives of the thesis

The specific objectives of the project include:

1. Review the current literature on the pertinent aspects of limestone pavements and climate change.
2. Establish a robust methodology for selecting limestone pavements to be investigated for this study.
3. Provide detailed analysis of grike microclimates using a data set extending for over one year.
4. Simulate the extent to which air circulation is influenced by the form of the grike.
5. Undertake a preliminary modelling exercise to provide a temperature simulation of the future grike microclimate.
6. Perform a descriptive survey of the invertebrates found in the grikes of limestone pavements studied, and provide analysis concerning depth.
7. Explore the potential for the limestone pavement grike to be considered a microrefugium in the context of future climate change.
8. Discuss the research which may be carried out in order to manage limestone pavements under climate change more effectively.

1.4 Thesis synopsis

1.4.1 Chapter One

Chapter One introduces the subject of the thesis, the key terms used and the current gaps in knowledge which require investigation. The aims, objectives and synopsis of the thesis are described.

1.4.2 Chapter Two

Chapter Two provides a review of the background literature explaining what a limestone pavement is, their genesis and distribution, factors that influence the geodiversity, microclimate and biodiversity of limestone pavements. The state of conservation and limestone pavement management are discussed concerning current threats and the threats which are facing limestone pavements in the future due to climate change.

1.4.3 Chapter Three

Chapter Three defines the philosophical grounding of the thesis regarding conservation philosophy and the methodological structure employed. The Methodology for selecting the sites for the study is discussed, providing the grounding in Willis' (2001) grouping system and critical success factors required for a viable site. A detailed description of each study site is provided concerning location, macroclimate, Geology, lithology, anthropogeography, biogeography, pavement Group and pavement character.

1.4.4 Chapter Four

A description of the methodology employed for selecting grikes, and deploying and collecting data from logging equipment are presented in Chapter Four. A description of the grike microclimates under study is provided concerning the stability of temperature, relative humidity and light intensity with depth into a grike over various time periods and severe weather.

1.4.5 Chapter Five

Chapter Five introduces the topic of computational fluid dynamics, and the relevance this has to grike microclimates. The methodology for simulating grike airflow is discussed, and the simulation parameters are defined. The results of the simulations are provided and explained to describe the types and strength of flow found in grikes of varying form.

1.4.6 Chapter Six

Chapter Six outlines the predictions derived from the United Kingdom Climate Projections 2018 (UKCP18) climate model and highlights the discrepancies between the macro and micro scale climate. Using the data collected in Chapter Four, Chapter Six details the method and results of regression modelling used to simulate the temperature of a grike based on external temperature, grike properties and temporal variables. This simulation is used to provide a series of probable temperature scenarios for grikes in various locations in Britain and Ireland over the next century.

1.4.7 Chapter Seven

Chapter Seven details the influence that depth has upon the fauna within subterranean environments and the methods which have been used to sample grike fauna. The methodology discusses the selection of grikes for study and how invertebrates were sampled and identified. An analysis of the invertebrate population and species distribution is provided regarding biogeography, depth and orientation. The discussion explores the effects of microclimate on invertebrate species, the invertebrates which may be able to maintain viable populations within the grike and may be maintained within a refugium of this size.

1.4.8 Chapter Eight

Chapter Eight discusses the findings that have emerged from this study and highlights the contributions that have been made to the current knowledge of the grike environment and the inhabitants of the deeper grike. This discussion is then used to provide the basis for suggestions of future research which may contribute to providing effective guidance for the management limestone pavements for climate change.

1.4.9 Chapter Nine

An evaluation of the extent to which each of the thesis' aims and objectives has been met is provided in Chapter Nine. This chapter also provides a summary of the key findings of this thesis and highlights the contributions they have made to the current state of limestone pavement research. A summarised critique of the limitations of this thesis is discussed, and it is suggested how further work would benefit this field of study.

2. Literature Review

2.1 Genesis and distribution of limestone pavements in the Britain and Ireland

2.1.1 Karst

Karst describes a landscape and set of features which are solutional in nature, owing to the interaction of water and soluble rocks such as limestone, marble, and gypsum (Waltham et al., 1997). Water acts over time to wear away at the soluble rocks creating fissures and sinkholes such that surface runoff and streams drain underground to continue to form underground karst caves. Highly soluble rock is not solely responsible for the production of karst. Structural and lithological features such as dense, massive, pure and coarsely fractured rocks are also important in the development of diverse karst scenery (Ford & Williams, 1989).

The word "karst" has been traced back to pre-Indo-European origins (Kranjc, 2001) from the word Kras in the Slovene language meaning rocky or stony. The term in its modern usage has been traced back to descriptions of phenomena similar to the “Kras Plateau” in Slovene which possessed several karstic features. Such descriptions were often made by German Scientists in the early 18th century, who called this place the “Karst Plateau” (Kranjc, 2001).

2.1.2 Limestone pavement formation

Chapter One explains the formation of limestone and the limestone pavement; this chapter develops these topics to discuss the diversity of limestone pavements found in Great Britain and Ireland. It is necessary to understand the subject in greater detail. Most of the limestone pavements in Great Britain and the Republic of Ireland were developed in Dinantian Stage (Lower Carboniferous) carbonate successions. After this time, in the Late Dinantian (Asbian to Brigantian) much of these isles had matured into a classical pattern of extensive flat-topped carbonate platforms under shallow water (Vincent, 1995).

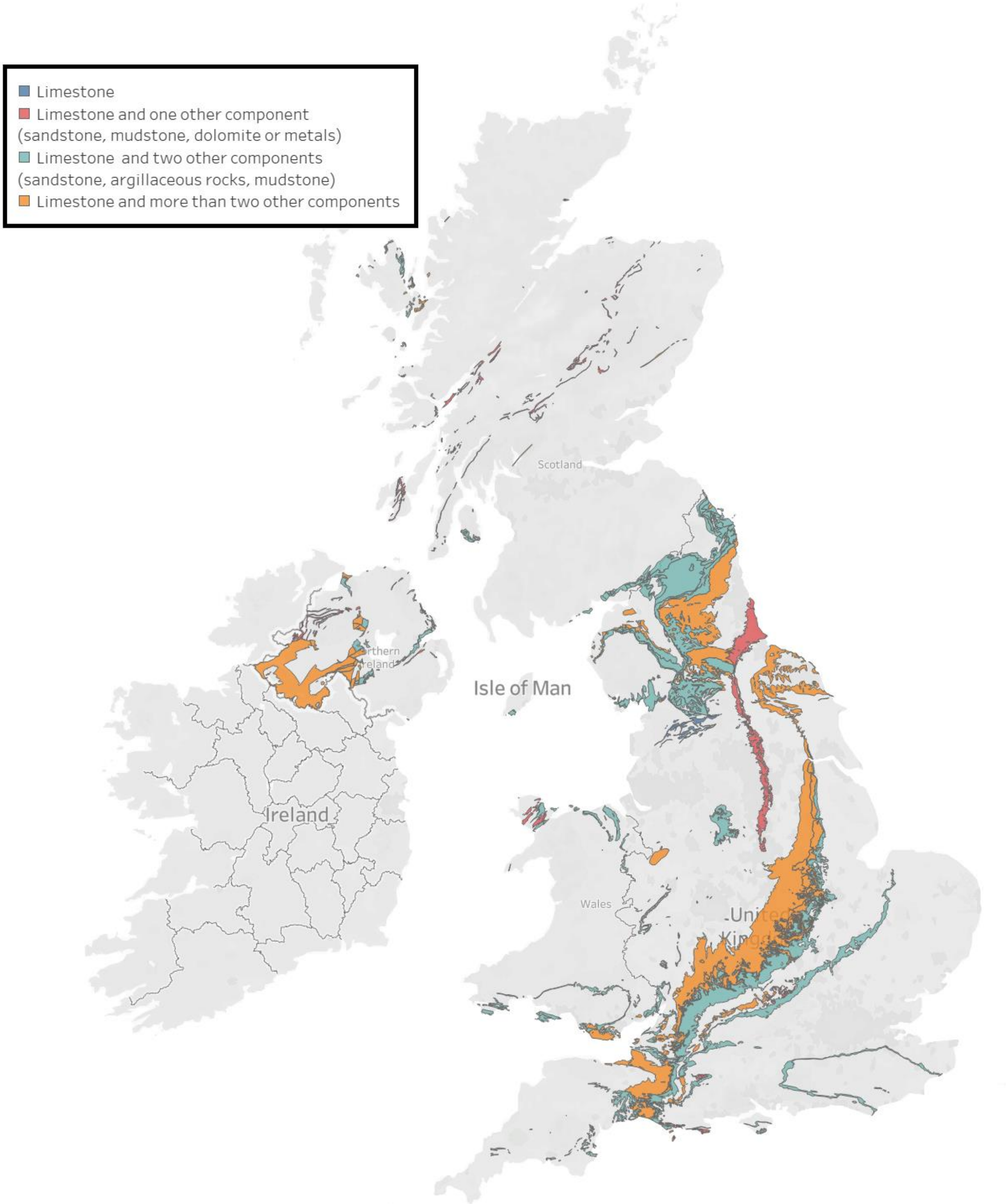


Figure 2.1 Bedrock Geology of the UK (British Geological Survey, 2018).

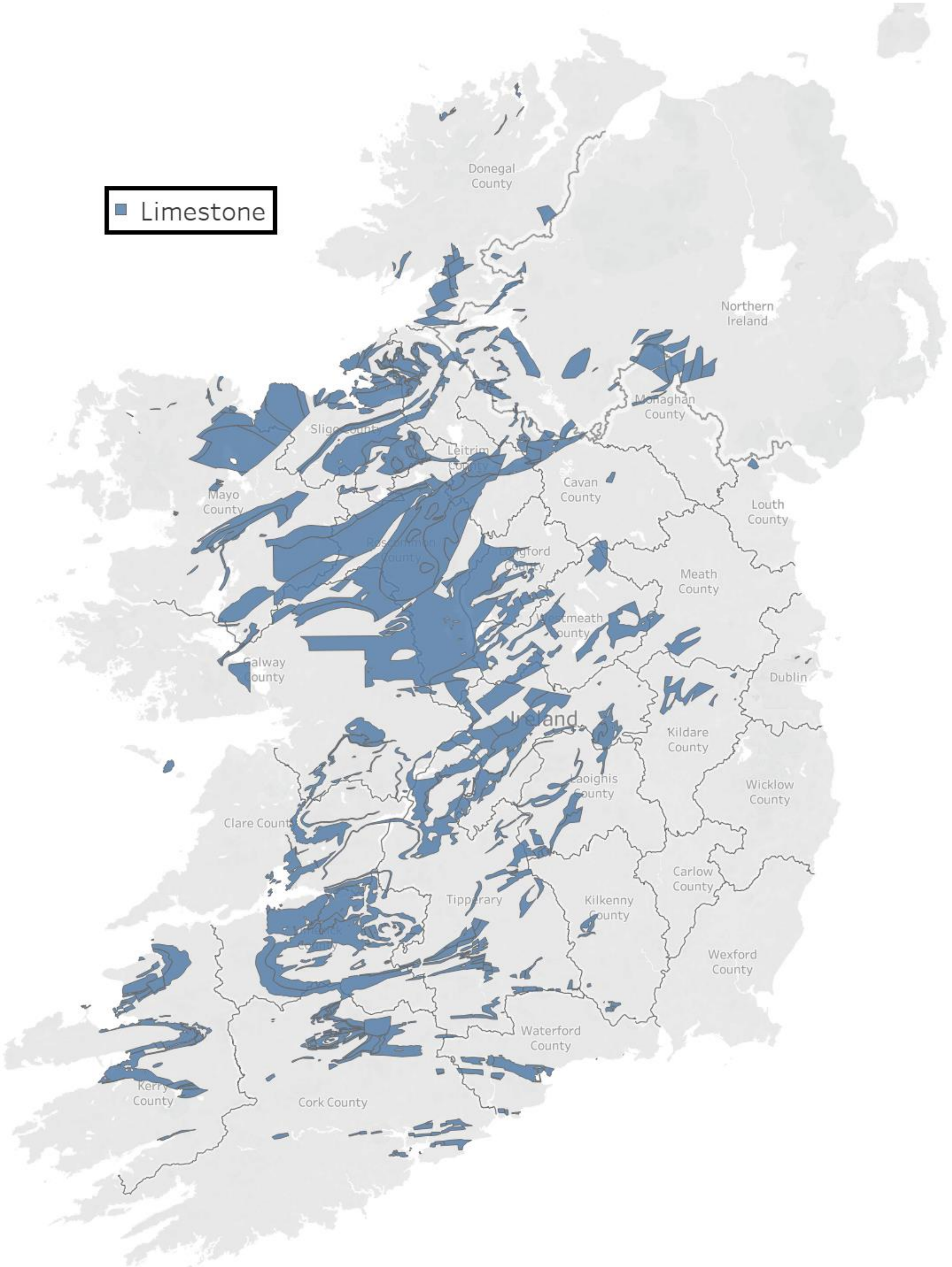


Figure 2.2 Bedrock Geology of the Republic of Ireland (Geological Survey, 2017).

The deposits occurring during the Dinantian period can be divided up into six major cycles of sea-level rise, including minor sub-cycles. Throughout these cycles, variable deposits laid down up to ten metres of sediment that were to become limestone (Vincent, 1995). During periods when the seas were shallower, the upper areas of exposed carbonate underwent complex pedogenic alteration due to a covering of volcanic dust. These exposed areas experienced the formation of calcretes which are associated with the creation of a more dense and hardened rock surface with relatively fewer joints. These limestone beds were covered over by further layers of material which was largely undisturbed until glaciation (Vincent, 1995).

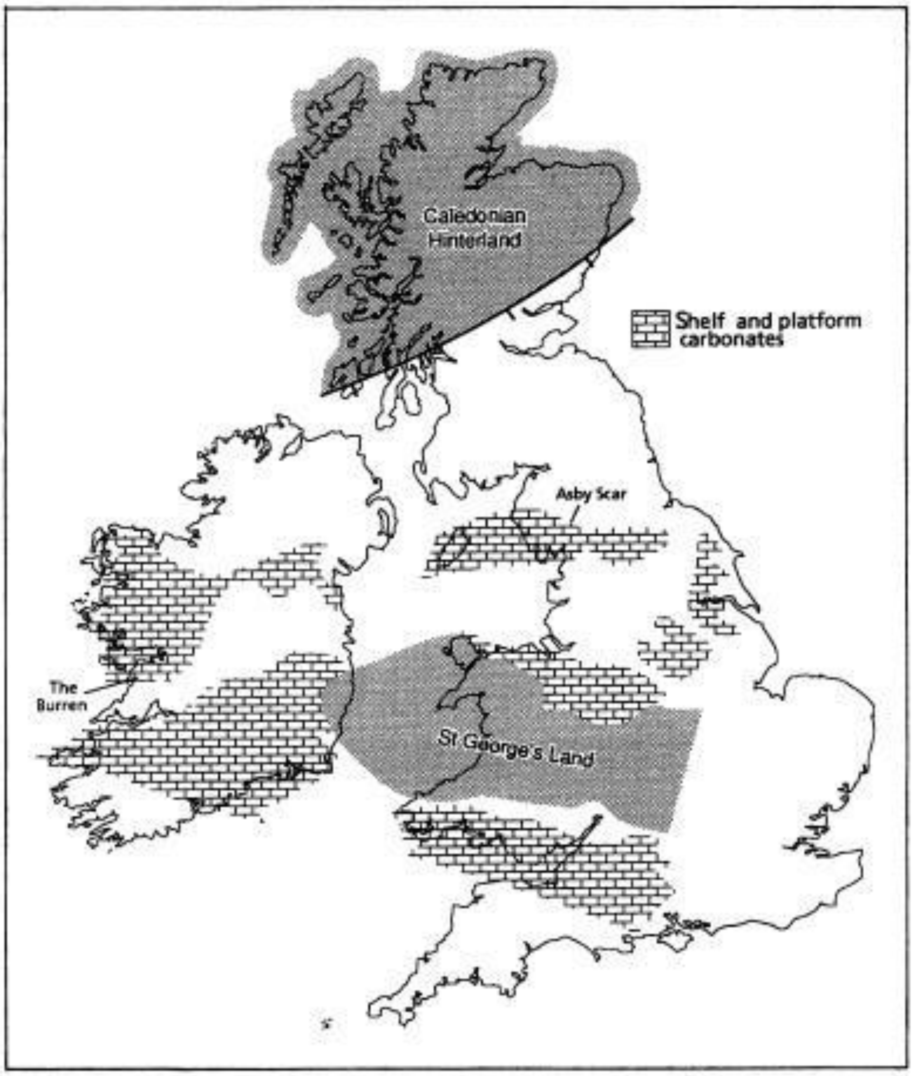


Fig. 1. Generalized Dinantian palaeogeography

Figure 2.3 Limestone pavements in the British Isles: a review (Vincent, 1995).

During the last glacial period in Britain and Ireland (110,000-12,000 years ago) ice progressed over parts of Britain and Ireland (Waltham et al., 1997). It is thought that over this period, the action of the ice advancing across the surface of the land ripped away the material covering the limestone. During glaciation, the more calcretized beds were more resistant to plucking and abrasion by the ice sheets and remained more fully intact (Vincent, 1995). Whereas as uncompacted, thinly bedded, or highly fractured limestones were more easily abraded and glacial erosion may have proved too severe to leave some extensive bedding-planes intact. Those pavements which are more thinly-bedded tend to be strongly affected by the action of mechanical weathering resulting in grikes which tend to be relatively shallow and narrow. In contrast, massively-bedded limestones tend to be more resistant and are intersected by deeper grikes that are often more than two metres deep (Sweeting, 1966). "In general, it is the massive limestone beds, which in some cases have undergone slight metamorphism, that produce the most extensive pavements" (Williams, 1966).

The depth of the limestone beds, resistance to glaciation and patterns in glacial advances combine to explain a great deal of the underlying history to the limestone on which limestone pavements form with such great variety. Further variety is determined by the conditions under which the limestone is eroded as explored in later discussions on solutional weathering.

2.1.3 What determines limestone pavement location?

Due to the requirement for a specific confluence of unrelated circumstances, the creation of limestone pavements is globally very rare. Despite their global scarcity, Britain and Ireland contain a great number of limestone pavements. The bulk of these pavements are situated in the Republic of Ireland which contains 32,187 hectares (Wilson & Fernández, 2013) and only 2,600 hectares in Britain at the last estimation in 1976 (Ward & Evans, 1976). In Britain and Ireland, the greatest extents of limestone pavement are on The Burren in the area of North Clare and South Galway to the west of the Republic of Ireland. Outside of Ireland, there are lesser expanses near to Ingleborough. However, smaller patches occur in and around the Lake District National Park, Sutherland, Scotland and in North and South Wales (Vincent, 1995; Waltham et al., 1997). Limestone pavement "units" have been grouped into "sites" in England and "areas" in the Republic of Ireland (Wilson & Fernández, 2013; Natural England, 2018). So as not to confuse terminology "area" will be used when referring to a group of limestone pavements as defended by the statutory authority.

Figure 2.4 Ice sheet coverage of Britain and Ireland (Clark et al., 2004).

Limestone pavements are notably absent from areas of Derbyshire (Burek, 1978), the Mendips (Jennings, 1971) and around Cork in the Republic of Ireland (Mitchell et al., 1973). Suitable bedrock underpins these areas but did not experience the erosion from ice sheets to produce limestone pavements (Jennings, 1971). Conversely, there are areas of Britain and Ireland which contain limestone bedding and were covered by ice but did not produce limestone pavement. It is hypothesised that this is due to the gradient of relief exceeding 45°; beyond which limestone pavement is less likely to develop. The exceptions to this hypothesis developed on Hutton Roof and at Great Asby Scar (Vincent, 1995).

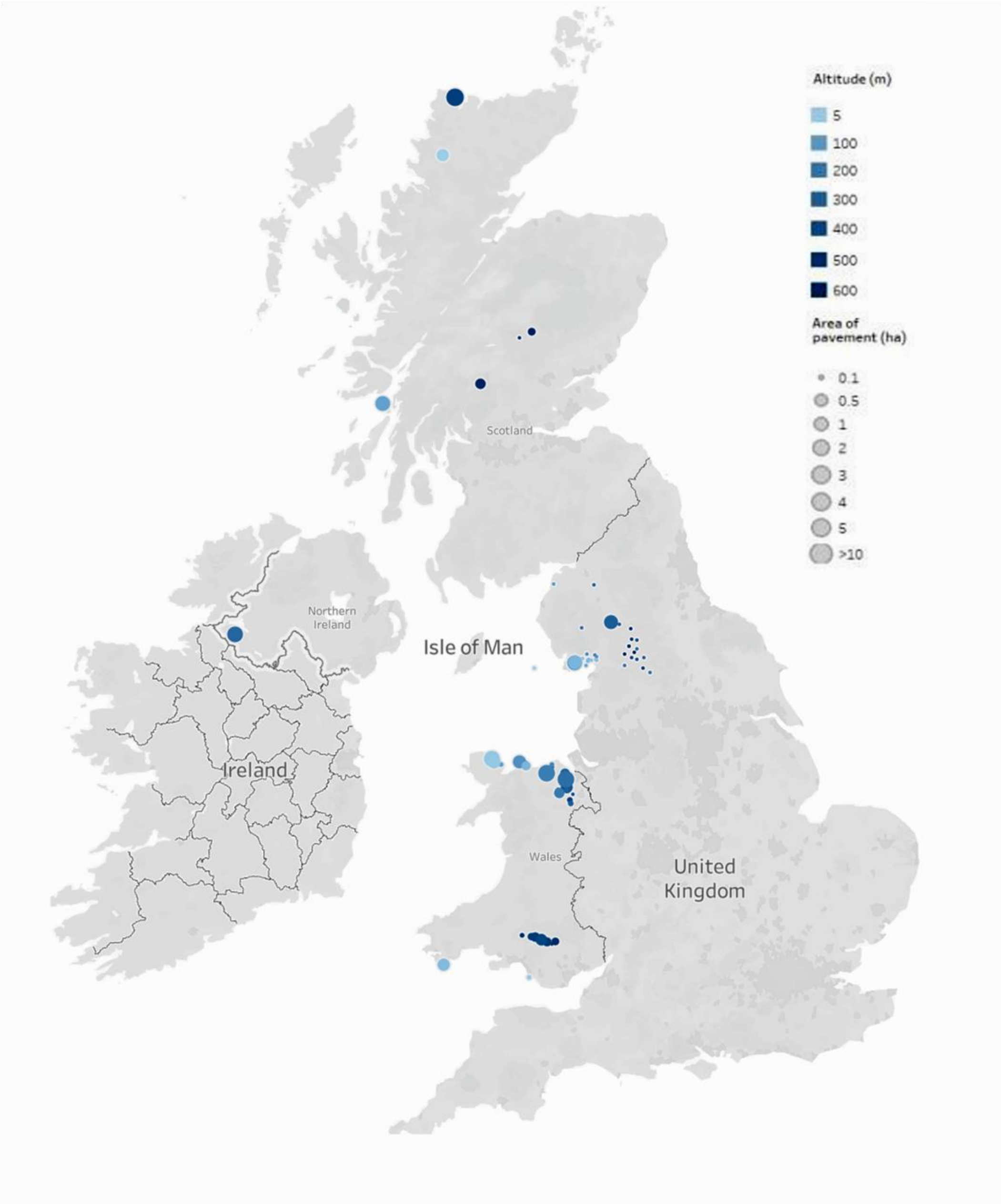
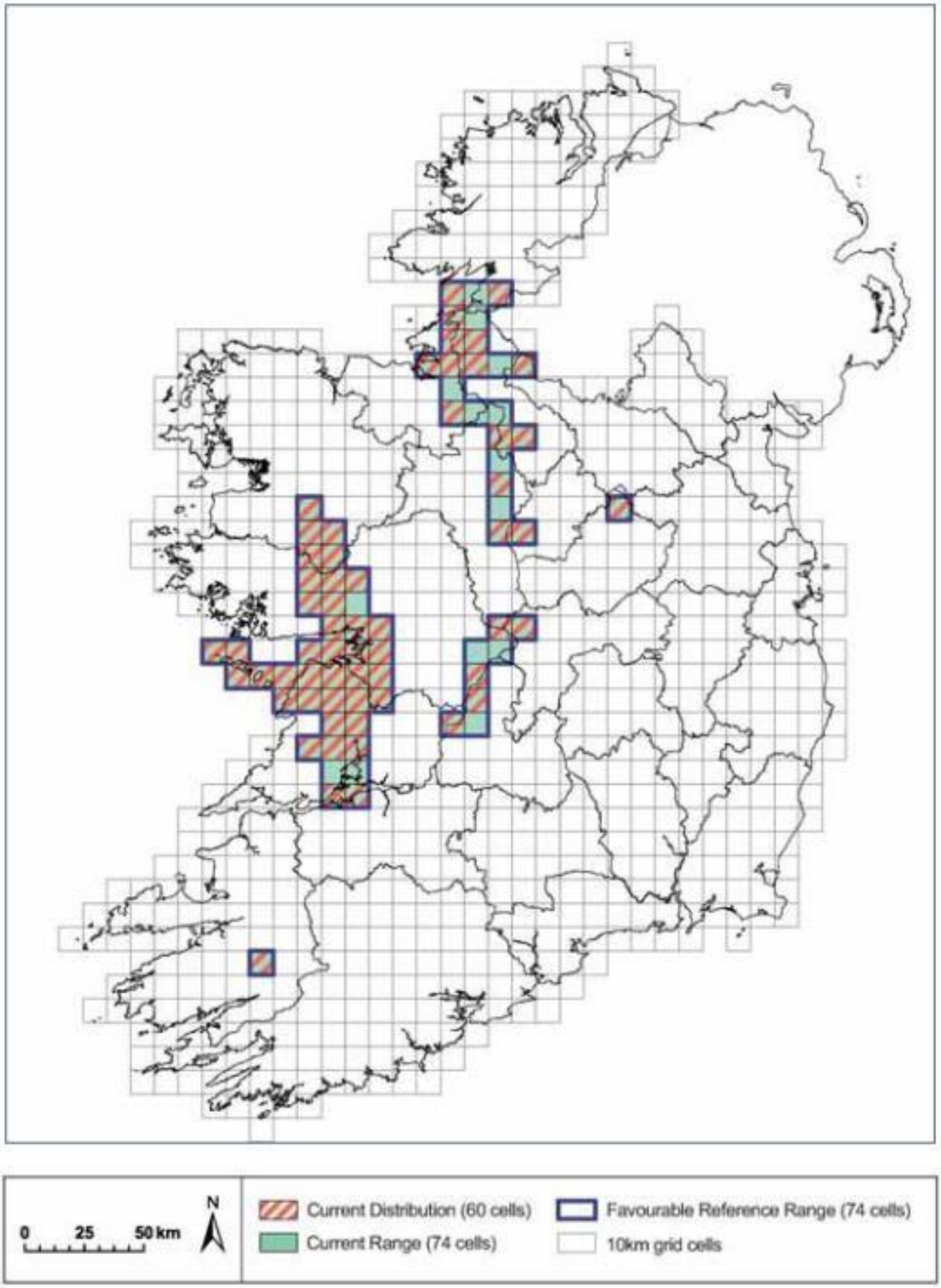


Figure 2.5 Location, altitude and extent of limestone pavement areas in the UK. (Natural England, 2018).



Limestone Pavement areas in the Republic of Ireland. (Pender, 2008)

2.1.4 What is solutional weathering?

Solutional weathering is the result of the interaction of acid often found in rainwater and the alkaline calcium carbonate ($CaCO_3$) making up a large part of the limestone.

Under one atmosphere of pressure carbon dioxide (CO_2) found in the air at a temperature of 25°C can dissolve at a concentration of 1.45g per litre of rainwater (Carroll, 2012). This concentration decreases with temperature yet creates a weak acid capable of acting upon the calcium carbonate. The quantity of calcium carbonate soluble in water is typically minute but varies with the strength of the acid, the temperature and the quantity of salt present in the solution (Carroll, 2012). Over time the solutional weathering of the calcium carbonate breaks down the limestone at its weakest points or where rainwater can pool. There is some evidence to suggest that over time, higher levels of precipitation will have the effect of removing greater amounts of limestone through solutional weathering (Williams, 1966). The relationship between precipitation and denudation is difficult to quantify due to the impacts of vegetation and substrate on the acidity of water interacting with the limestone (Williams, 1966; Zseni, Goldie & Bárány-Kevei, 2003). In humid climates such as those featuring in this study, the dissolved calcium carbonate and detrital constituents of the limestone form soils and in time form a black soil known as rendzina (Carroll, 2012).

$$H_2O + CO_2 \rightarrow H_2CO_3 + (HCO_3)^-$$

Water + Carbon dioxide → Carbonic acid

Production of carbonic acid

$$CaCO_3 + H^+ + (HCO_3)^- \rightarrow Ca^{2+} + 2(HCO_3)^-$$

Calcium carbonate + Hydrogen ion + Carbonic acid → Calcium bicarbonate (in solution)

Limestone reaction

(Carroll, 2012)

Grikes which develop in conditions exposed to the air are jagged and sharpened by more selective corrosion compared to more rounded forms which have formed under a soil or peat cover. If developing under cover of soil, the limestone is also exposed to greater levels of acidity, which increases further with the depth and acidity of the type of soil covering or deposits of acid vegetation (Zseni, Goldie & Bárány-Kevei, 2003).

Greater levels of acidity should, in theory, result in a greater degree of weathering and deeper grikes; however other factors such as soil texture, slope and tree cover can lessen the weathering or secure soils so that a pavement never forms (Zseni, Goldie & Bárány-Kevei, 2003). In combination, the formation and resultant character of the limestone and nature of its weathering contribute to creating a wide variety of limestone pavements in Great Britain and the Republic of Ireland. Exposed limestone pavements continue to experience weathering due to solutional weathering and the action of lichens (Trudgill, 1985).

2.1.5 What defines a limestone pavement and its features?

Willis (2011) has explored the definition of the limestone pavement habitat, which does not need repeating in this review. In this work, the most recent and most appropriate definition for the limestone pavement as a habitat has recognised the importance of the grike microclimate in the proposed definition. "A partially or wholly exposed area of limestone, fissured by natural erosion into a pattern of clints and grikes, with a distinctive and unique plant community which characterises the microclimates of the grikes"(Willis, 2011).

Clints are the blocks of limestone that constitute the paving, and grikes are the open crevices isolating the individual clints (Jain, 2014). The words "clints" and "grikes" are of Yorkshire dialect origin but are now almost out of use except in scientific literature. The most dominant grike systems run almost north to south (NS), but there is a less-developed, secondary system at right angles to this running east to west (EW) (Jennings, 1985). Grikes vary in both width and depth. From a sample of 42 UK limestone pavements it has been observed that grikes reach over 2m in both depth and width, but most are considerably narrower and shallower falling within a mean of 0.6m deep and 0.3m wide (Willis, 2011).

This study deals individually with the form and resultant microclimate of the grike. In order to outline the subject of this thesis, the form of the grike has been explored through definitions of the grike structure. Grikes or kluftkarren have been described in many ways; most deal with the shape and formation of the grike.

- “Grikes (or Kluftkarren) are fissures, joint or fault guided, which have been opened by solution” (Zseni, Goldie & Bárány-Kevei, 2003).
- “a complex of deep crevices known as grikes” (Backshall, Webb & Jerram, 2001).
- “elongated hollows between the blocks of rock” (Silvertown, 1982).
- “a pattern of deep intersecting fissures ('grikes') formed by solution of the joint planes” (Colebourn, 1974).
- “deep vertical fissures” (Jain, 2014)

Some definitions allude to the microclimate found within grikes

- “shaded fissures in the limestone” (Osborne, Clabby, Horsley & Nolan, 1994)

One definition combines structural features with, formation and ecology

- “Grikes are approximately rectangular compartments with vertical sides and vary in width, depth and length. A fine mull or rendzina soil is found at the bottom of most grikes and in crannies and solution hollows formed in the side walls. The grikes of most limestone pavements contain vascular flora of plants typical of woodland, with some species which are characteristic colonisers of exposed rocks and walls.” (Silvertown, 1983)

2.2 The Grike microclimate

In order to understand microclimate, it is imperative to understand what is meant by climate. Climate is most commonly referred to as the sum total of the weather conditions which prevail within an area, encompassing temperature, humidity, wind velocity and precipitation. Within this definition, the climate can be considered to be the weather conditions of an area for a period of 30 years, known as “normals” (Barry & Hall-McKim, 2014; WMO, 2017).

Microclimates are commonly defined as “the suite of climatic conditions measured in localised areas” (Geiger, Aron & Todhunter, 2009). Similar to climate, the microclimate is considered over an extended period of time; however, this period is defined by the forcing factors which define each microclimate (Camuffo, 2013). Within a microclimate, conditions can alter dramatically over very short distances, and organisms can influence the microclimate in which they are found (Stoutjesdijk & Barkman, 2014). Changes to microclimates are reported to result from several causes; these include localised differences in heating, water availability, wind-speed, evapotranspiration and shading (Stoutjesdijk & Barkman, 2014; Jones, 2013).

The first mention of a sheltering microclimate found within a grike known to the author was in 1910 by Phillips, who describes snails' retreat to the grikes in warm weather (Phillips, 1910). Since then, microclimate has been identified as the cornerstone to the distinctive community of plants and animals found within grikes (Silvertown, 1982, York, 2009). Most recently, microclimates have been recognised in the proposed definition of a limestone pavement by Willis (2011) quoted above. Several authors have also studied the grike microclimate, each of which has uncovered new aspects of this habitat.

2.2.1 A thermally stable habitat

The limestone pavement grike is an extremely climatically stable area. Early temperature data from Silvertown (1982) on the Malham Tarn limestone pavement on an undocumented date, shows that over a day the temperature at the surface of the grike may fluctuate from as little as 8°C at 6:00 to 28°C at 17:00. Whereas over the same period the temperature at the bottom of the grike 70 cm from the surface escalated only from 8°C at 6:00 to a maximum of 15°C at noon.

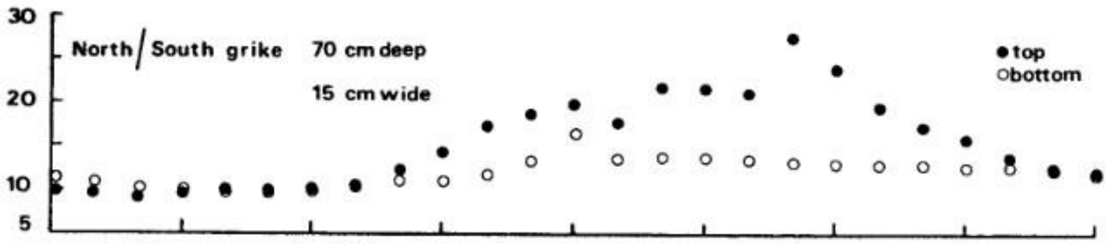


Figure 2.6 Temperatures recorded from the top and bottom of a 70 cm deep grike (adapted from Silvertown, 1982).

A number of other studies have corroborated this finding, each identifying that over the course of the day, the temperature in a grike became more stable as the distance from the surface increased (Heslop-Harrison, 1960, Dickinson, Pearson & Webb, 1963; Burek & Legg 1999; Alexander, Burek & Gibbs, 2007). The mechanisms causing the stability of climate are not yet fully understood. However, it is hypothesised that the increasingly limited exposure of the grike to the sun as depth increases has a part to play in maintaining a temperature which is less affected by diurnal solar radiative heating (Burek & Legg, 1999). The limestone also insulates the grike from changes in surface temperature. Limestone's thermal conductivity averages 0.17 W/mK at 300K; in context, this is around double the insulating property of marble (Robertson, 1988).

The resilience of the grike microclimate is likely to be of increasing importance as the incidence of severe weather events increase (Pachauri et al., 2014). Severe weather can present an equally extreme cost to species, resulting in population crashes in response to unusual conditions (Jentsch & Beierkuhnlein, 2008; Orsenigo, Mondoni, Rossi & Abeli, 2014; Palmer et al., 2017). Similar temperature stability has been observed in dolines or sinkholes that are conical depressions or shafts formed in karst areas (Monroe & Wicander, 2011). These dolines allow less heat-tolerant plants a greater chance of surviving during a warmer global climate (Bátori et al., 2014). The stability of the grike's temperature is one of the most important features indicating that it may also protect less heat-tolerant plants and animals from climatic excesses in the future (Stevenson, 1985).

2.2.2 A low-temperature change velocity

It was demonstrated by Silvertown (1982) that diurnal temperature changes are attenuated inside the grike. It has also been shown that this stabilisation of temperature occurs over several months (Alexander, Burek & Gibbs, 2007). It can be observed in Figure 2.7 that over a year, the temperature at the bottom a 196cm deep grike in Cumbria changes more gradually than at the surface.

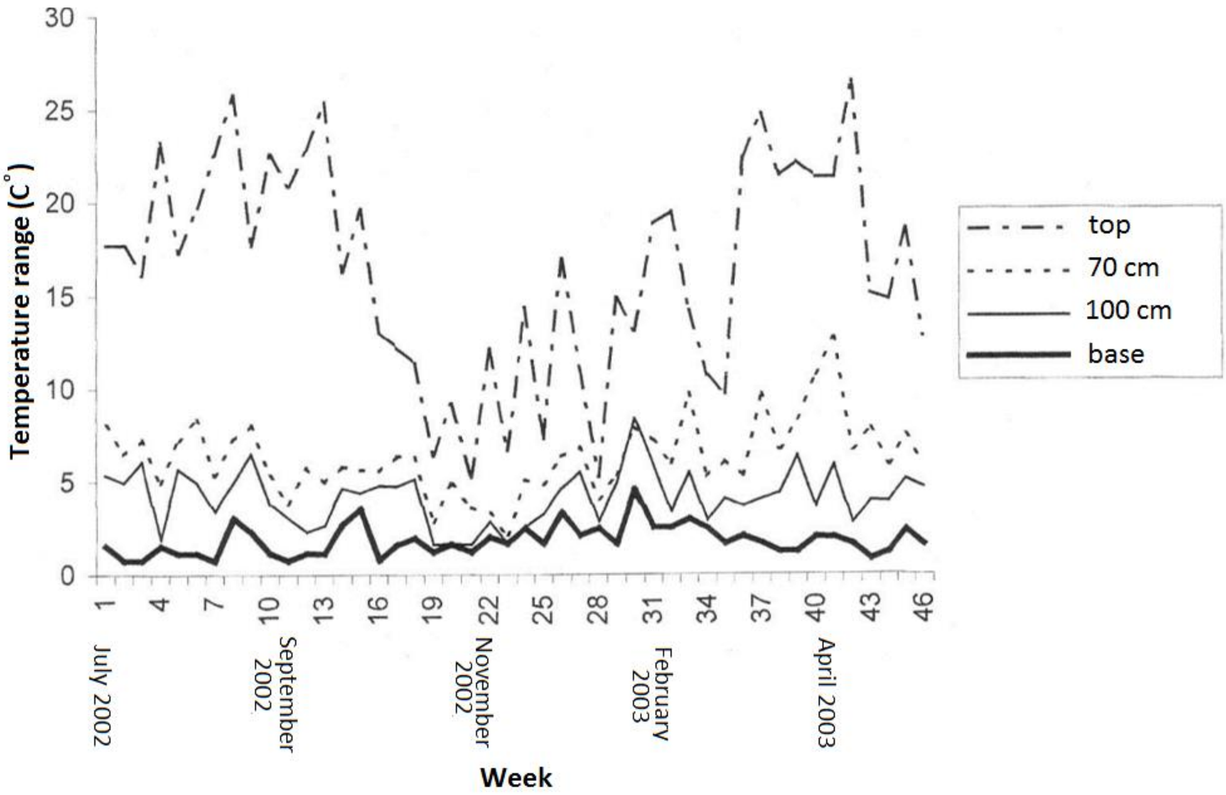


Figure 2.7 Weekly grike temperature range in Cumbria at each of the four depths within the north-south grike (Alexander, Burek & Gibbs, 2007).

Further observation in the same study taken from Holme Park Quarry in Cumbria over ten months from July 2003 to April 2004 shows the difference in temperature from the surface to the bottom of a north-south orientated grike of 196cm deep (Figure 2.8).

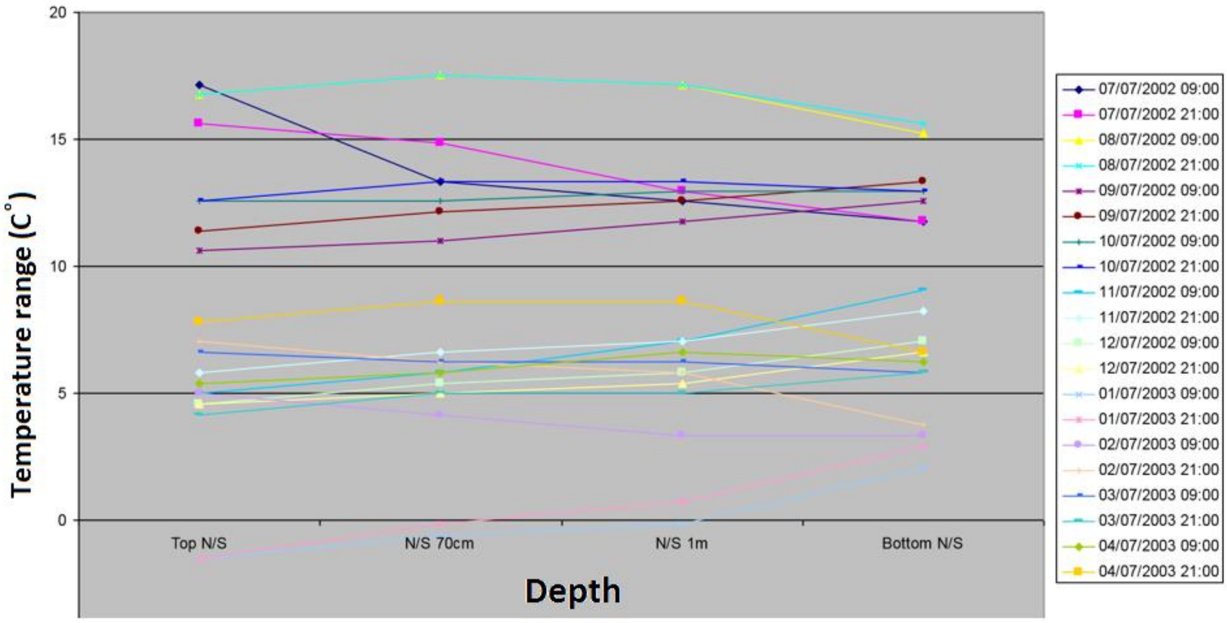


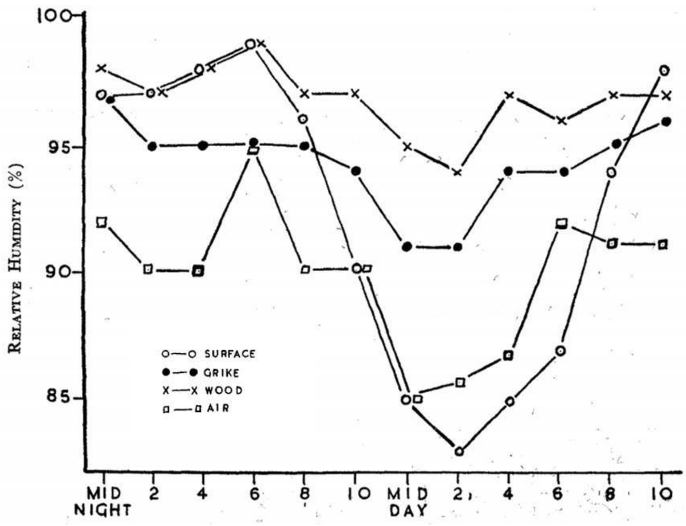
Figure 2.8 Temperature taken from a range of depths on Holme Park Quarry limestone pavement (Alexander, Burek & Gibbs, 2007).

Both examples show that the temperature at the bottom of the grike is more stable than that at the surface over a period of time. The measurements which are taken from Holme Park Quarry also show that a change in temperature at the bottom of the grike occurs after a time lag when compared to the surface.

Although several studies have shown the stability of the grike microclimate, there has been no long term study known to the author to observe a whole year, nor has the time lag in temperature change within a grike received detailed study.

2.2.3 High and stable humidity

Some of the earliest papers describing the grike microclimate recorded the relative humidity from several areas over The Burren (Dickinson, Pearson and Webb, 1964; Heslop-Harrison, 1960). Measurement of relative humidity took place on several sites around The Burren under drought conditions from the 25th to 27th May 1959 (Heslop-Harrison, 1960). Relative humidity (converted from vapour pressure deficit) within one grike was reportedly 43.03% at the surface and increased to 50.87% at 30 cm and 72.87% at the 115cm base of the grike (Heslop-Harrison, 1960). Later experimentation on The Burren recorded relative humidity over a day in grikes; Figure 2.9 shows the mean figures from six days during August 1961 (Dickinson, Pearson and Webb, 1964).



○ Surface humidity is taken no more than 15 cm from the surface of the grike.

● Grike relative humidity is the mean figure from grikes between 5 and 50 cm deep and 10 to 25 cm wide.

x Wood humidity is taken from a nearby forest

□ Air temperature is taken from a meteorological station one kilometre from the experimental site.

Figure 2.9 Mean relative humidity from three environments over six days during August 1961 (Dickinson, Pearson and Webb, 1964).

This figure shows that the relative humidity of the grike is more stable and often higher than that of the surface, and like the temperature of the grike, changes in relative humidity occur in the grike after they have occurred on the surface. It is indicative from the evidence that the soil moisture within grikes may also be relatively high and measurements and samples of grike soil confirm this (Dickinson, Pearson and Webb, 1964; Willis, 2011). The relative humidity and soil moisture of the grike is more similar to that of a forest than the surface of the pavement as has been stated by other authors (Heslop-Harrison, 1960; Dickinson et al., 1963; Silvertown, 1982).

Although the grike retains moisture in a drought, the degree of drought has not been quantified. To the author’s knowledge there has been no long-term study of relative humidity in a grike over a year, nor has relative humidity been observed at depths of more than two metres as found in The Burren.

2.2.4 Variety in grike orientation which results in microclimate diversification

Slope, orientation and gradient have a large impact on the microclimate of habitats by moderating the heat and light received through solar radiation (Geiger, Aron, & Todhunter, 2009). This impact is such that plant communities with low-temperature requirements are found in greater number on north-facing slopes in the northern hemisphere (Maclean et al., 2015). Research has shown that northern hemisphere solar panels receive the greatest levels of light absorption when angled in a southerly direction (Benghanem, 2011); however, the opposite is true in the southern hemisphere (Yan, Saha, Meredith & Goodwin, 2013).

Grikes are often orientated at ninety degrees to one another (Goldie & Cox, 2000) and therefore present different aspects of the grike body to the sun at any one time of day. The difference of orientation causes a measurable difference in the microclimate found in a North-South (NS) facing grike when compared to an East-West (EW) facing grike, over 24 hours.

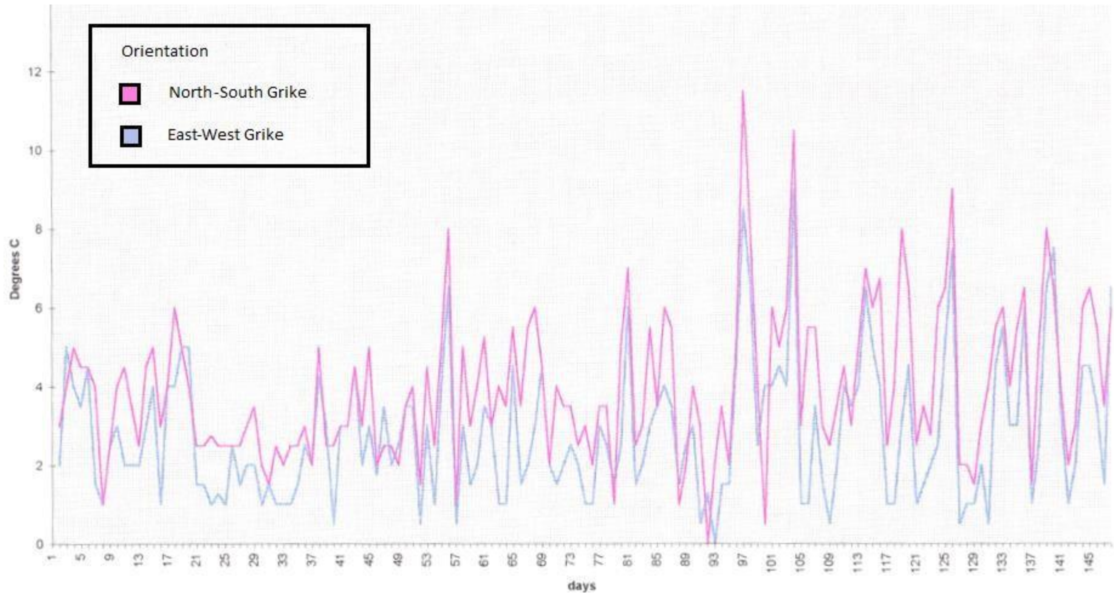


Figure 2.10 Temperature recorded at the base of grikes in Y Taranau from 3rd September to 22nd December 1998 (Burek and Legg, 1999).

Figure 2.10 shows that temperature is almost always higher in the north-south orientated grike. This led to the realisation that an east-west orientated grike only receives sun directly down the length of the grike in the early and late hours of the day, whereas a north-south orientated grike receives direct sun at midday. The differing exposure to light is hypothesised to result in a higher overall temperature in the north-south grike because it receives direct light when the sun is most intense (Alexander, Burek & Gibbs, 2007). Silvertown (1982) also postulated that the orientation of grikes might influence seasonal differences in microclimate.

Though there has been evidence to show that there is a relationship between temperature and light intensity and that light and temperature are both influenced by grike orientation (Alexander, Burek & Gibbs, 2007), to the author's knowledge, there has not yet been a study of over a year which explored this property from a diverse set of different limestone pavements.

2.2.5 A solid structure of limestone which alters the airflow

The main structural features of a limestone pavement are the limestone blocks providing shade and insulation to the grikes. Little systematic research has been conducted to understand how the shape of the limestone pavement influences the impacts of light and air on the grike microclimate; however, it is often alluded to in relation to the exposure experienced by plants and animals in the grike. Heslop-Harrison relates that on The Burren, the unshaded vegetation can dry when exposed to wind and that even shallow fissures found on limestone pavements can provide valuable shelter (1960). Colebourn (1974) references spider webs catching air currents in a grike and eddies in wider grikes restricting web formation. Outside of mentions of the effect of the grike on air passage, there is no work known to the author that directly measures these phenomena. This type of shelter is not unique to the grike, and it may be possible to make inferences from similar habitats and structures.

Limestone caves and grikes share a subterranean karst geodiversity where the entrance restricts airflow, and thermally stable limestone surrounds the chamber. A similar decrease in turbulence is exhibited in the microclimate of cave entrances based upon multiple measurements. The gradient in the observed air density becomes shallower with depth into the cave; this is indicative of less air movement (Domínguez-Villar, 2015). A decrease in air movement with increased cave depth has also been demonstrated using tracer gas experiments (Gregorič, Zidanšek & Vaupotič, 2011) and flow velocity investigations (Brodny & Tutak,2016). The airflow within a cave mouth is theorised to be driven by differential pressure between the cave and outside environment creating a graduated decrease in airflow with distance from the cave mouth (Wigley & Brown, 1976). The airflow in grikes has been hypothesised to have “two air layers”. A turbulent layer may be formed at the surface where the air in the grike and outside the grike has free contact. Below this, there is suggested to be a lower and more stable, layer making up two-thirds of the grike, where temperature and relative humidity are more stable than in the higher layer (Yarranton & Beasleigh, 1969).

Structurally similar arrangements such as ploughed furrows and street canyons have however received large amounts of research, and present possible parallels to the grike. Street canyons are the gaps between large rows of buildings and skyscrapers such as New York’s 5th Avenue. The orientation and ratio of canyon height to the width of a street canyon has been observed to influence the amount of light reaching the street, which influences temperature felt by pedestrians (Ali-Toudert & Mayer, 2006). Similarly, Geiger, Aron & Todhunter (2009) found the temperature at the bottom of a furrow was on average 2°C lower than further up the side of the furrow. The difference in temperature is attributed to the upper slope receiving much stronger solar radiation than the lower areas.

Street canyon model research shows that in a deep canyon a wind flowing perpendicularly over the top of buildings creates a vortex in a canyon's upper reaches, the influence of which decreases with depth (Figure 2.11) (Murena, Favale, Vardoulakis & Solazzo, 2009). As the canyon width increases the vortex increases in diameter and decreases in speed (Figure 2.12) (Simoëns, Ayrault & Wallace, 2007).

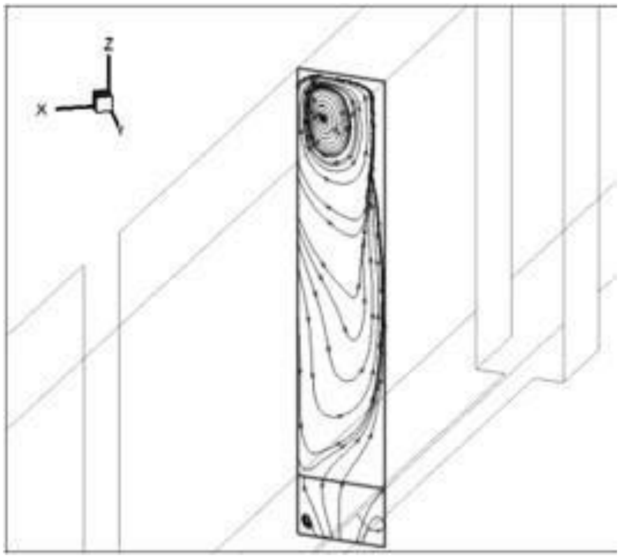


Figure 2.11 Flow field diagram of a street canyon cross-section where the wind is blowing almost perpendicularly to the street (Murena, Favale, Vardoulakis & Solazzo, 2009).

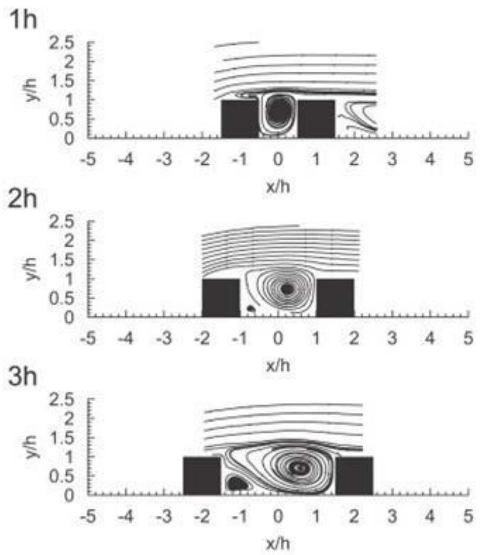


Figure 2.12 Flow field diagram of a widening street canyon cross-sections where the wind is blowing perpendicularly to the street (Simoëns, Ayrault & Wallace, 2007).

Street canyons are not a perfect parallel to grikes. Within canyons, solar radiative heating of the floor and walls in a street canyon provide a pressure difference forcing warmer air to rise on the warmer side of the canyon and fall on the cooler side. The vortex created by this heating can contribute to, or counter any other vortex created by the wind (Xiaomin, Liu & Leung, 2007). Street canyons also experience warming from the traffic and streets at their base which introduces heating anomalies not experienced in a grike (Wedding, Lombardi & Cermak, 1977; Murena, Favale, Vardoulakis & Solazzo, 2009).

2.3 Biodiversity

2.3.1 Limestone pavement biodiversity

Limestone pavements often form a part of a wider ecosystem (Willis, 2011). The plant community found within limestone pavement habitats are recognised as characteristic of the exceptional grike structure created by their geomorphological and geological features (Ward & Evans, 1976). The definition of the terms community and assemblage in this thesis will be derived from Stroud et al. (2015) where a community is “a group of interacting species populations occurring together in space” as opposed to an assemblage which is “a taxonomically related group of species that occur together in space and time”.

Open limestone pavements without large vegetation provide stable subterranean microclimates which harbour plant species normally associated with forests (Webb, 1961). Limestone pavements in different locations have been identified to have unique variations in grike floral community, due to differences in climate and lithology (Joint Nature Conservation Committee, 2019).

The collection of species associated with the limestone pavement habitat and their grikes include several rare and scarce vascular and non-vascular plant species, lichen and even some scarce invertebrates. One such example from Yorkshire in Great Britain is the Downy currant (*Ribes spicatum*), where limestone pavements are known to contain a significant percentage of the population (Usher, 1980). A further example is Mouse-ear cress (*Arabidopsis thaliana*), which was recorded to be common on limestone pavements in The Burren but rarely found in other natural habitats in the Republic of Ireland (Webb, 1961). The Rigid Buckler-fern (*Dryopteris submontana*) population in the UK is also thought to be almost entirely confined to limestone pavements. This species was once widespread in upland areas of Snowdonia and Arran. Due to grazing pressures, 80% of this species reside within the grikes of limestone pavement which afford a degree of protection from grazing (Gilbert, 1970; Wardlaw & Leonard, 2002). Research from The Burren has shown that solution hollows on the limestone grike contain a community which does not bear a resemblance to that of the surrounding vegetation and varies based upon the phase of development as plants become more established (Ivimey-Cook, 1965). Table 2.1 contains several examples of rare species found on limestone pavements of the British Isles.

Table 2.1 Examples of threatened species found on limestone pavements in Great Britain and the Republic of Ireland (Webb, 1961; Natural England, 2001; Wilson, 2013; National Parks & Wildlife Service, 2016; Joint Nature Conservation Committee, 2018; Botanical Society of Britain and Ireland, 2016).

	Rarity Republic of Ireland	Rarity Britain
Angular Solomon's-seal (*Polygonatum odoratum*)	Not found	Least Concern (Nationally Scarce)
Baneberry (*Actaea spicata*)	Not found	Least Concern (Nationally Scarce)
Bird's foot sedge (*Carex ornithopoda*)	Not found	Least Concern (Nationally Rare)
Dark-red helleborine (*Epipactis atrorubens*)	Least Concern	Least Concern (Nationally Scarce)
Downy red currant (*Ribes spicatum*)	Not found	Least Concern (Nationally Scarce)
Fingered sedge (*Carex digitata*)	Not found	Least Concern (Nationally Scarce)
Hairy violet (*Viola hirta*)	Vulnerable	Least Concern
Irish whitebeam (*Sorbus Hibernica*)	Vulnerable	Not found
ladies' tresses (*Spiranthes spiralis*)	Near Threatened	Near Threatened
Limestone fern (*Gymnocarpium robertianum*)	Critically Endangered	Least Concern (Nationally Scarce)
Narrow-leaved bitter-cress (*Cardamine impatiens*)	Endangered	Least Concern (Nationally Scarce)
Pale St. John's-wort (*Hypericum montanum*)	Not found	Near Threatened
Rigid Buckler-fern (*Dryopteris submontana*)	Not found	Least Concern (Nationally Scarce)
spring gentian (*Gentiana verna*)	Near Threatened	Vulnerable
Wood small-reed (*Calamagrostis epigejos*)	Vulnerable	Least Concern

Many of the floral species found on limestone pavements have fauna associated with them. The threatened Duke of Burgundy butterfly (*Hamearis lucina*) lays its eggs on the underside of cowslip (*Primula officinalis*) associated with the Morecambe bay limestone pavements (Natural England, 2013). Bird's-foot Trefoil (*Lotus corniculatus)* like many others of its genus is a popular nectar plant to butterflies. Bird's-foot Trefoil has been linked to two Biodiversity Action Plan (BAP) priority species, the Pearl-bordered Fritillary butterfly (*Boloria euphrosyne*) and the Grayling butterfly (*Hipparchia semele*) at Wharton Crag and Gait Barrows limestone pavements respectively **(**Butterfly Conservation, 2016)**.** Bird's-foot Trefoil is also closely linked with the life cycle of the western mason bee (*Osmia parietina*) which is another BAP priority species*.* As well as being one of the bee's major food sources, the nectar of the flower is also inserted into egg chambers made in exposed limestone faces (Scottish Natural Heritage, 2013). The Burren is the only known location in the Republic of Ireland for The Burren Green Moth (*Calamia tridens*) which feeds on *Sesleria caerulea* which is abundant in the area (Webb, 1961; Waring & Townsend, 2017).

The invertebrate life of limestone pavements has received targeted study in several areas. Some studies have specifically looked at certain behaviours such as the cyanobacteria cropping behaviours of snails found in Sweden (Fröberg, Baur & Baur, 1993; Baur, Baur & Fröberg, 1994; Baur & Baur, 1995; Hesbacher et al., 1995) or web building in the grike mouth by spiders (Coleburn, 1974). Other studies have specifically targeted the presence of particular species such as snails and woodlice, which associate with limestone pavements due to the required calcium for their shells and carapaces (Platts, 1977; Killeen, 1997; Lloyd-Jones, 2001). Among the many species that thrive within the grike are two BAP priority species, the Upland pill-woodlouse (*Armadillidium pictum)* (Natural England, 2013) and narrow-mouthed whorl snail (*Vertigo angustior*) (Killeen, 1997).

2.3.2 Biodiversity and microclimate

<u>2.3.2.1 Bats in caves</u>

Caves may be considered a structurally similar habitat to a grike, as they contain an air chamber surrounded by thermally stable rock and have limited microclimatic interaction with the outside environment through a restricted opening. Caves are one such environment where the role of microclimate and the distribution of species interact measurably and may provide insights which are pertinent to understanding similar relationships in grikes (Clark et al., 1998; Briggler & Prather 2003; Hayes et al., 2011). Bats and their choice of cave roost location have received study from several authors. Many species of bats spend most of their time within caves, and much of this is spent sleeping or in a deeper state of torpor. Although bats can thermoregulate through movement, social grouping and reduction in surface area (Hannon & Ruth, 2014) much of their time in torpor is spent close to ambient temperature (Perry, 2012). Bats' lack of thermoregulation in a state of torpor makes them extremely sensitive to changes in microclimate but perhaps not as sensitive as invertebrates, which are completely exothermic. The bat's sensitivity to microclimate is observed in their choice of roost temperature, relative humidity and airflow (Furey & Racey, 2016). Numerous studies have suggested that different species of bat favour different microclimatic ranges (Clark et al., 1998; Briggler & Prather 2003; Hayes et al., 2011). Bats are very sensitive to temperature fluctuations, however because of their small body size they are also sensitive to water loss (Hannon & Ruth, 2014), although as with temperature bats can manage their water loss through behavioural means. Our understanding of different species' microclimatic needs is still developing as studies are finding bat species' differing requirements for water balance (Baudinette et al., 2000) and comparative importance of relative humidity and temperature (Paksuz, Özkan & Postawa, 2007).

2.3.2.2 Invertebrates in caves and other niche microclimates

The influence of microclimate on individual Invertebrate orders has not received as much notice as bats; however, as a collective, there is a large amount of research about invertebrate relationships with microclimates. As has been mentioned previously, invertebrates are exothermic, and their wellbeing is highly influenced by the microclimate in which they are situated. Simple preferences for microclimates have been found by comparing the absence and presence of certain species (of millipede) between different microclimates (Bogyó et al., 2015). Preference for a variety of microclimates has also been shown using species diversity indices, which give an estimate of the number of different species within a community (Magurran, 2013; Pellegrini & Ferreira, 2016). The sensitivity of interactions between invertebrates and microclimates have been used to observe the impact of habitat change in the case of tree felling on beetles (Seibold et al., 2016; Thorn et al., 2016) and the influence of "invasive" plant species on the snails' habitat microclimate (Ruckli, Rusterholz & Baur, 2013).

Caves provide several situations in which invertebrates show preferences for specific microclimates. Spider, moth, cockroach and mite distribution have all received a certain amount of study within caves (Weinstein, 1994; Welbourn, 1999; Pellegrini & Ferreira, 2016). Like bats, there are nuances in the species microclimate interaction which present areas for interest. Under certain circumstances, moths are influenced by severe weather such as heatwaves and high precipitation. On these occasions, moths adjust their position within a cave, in reaction to the impacts these events have on the cave microclimate (Ferreira, 2015). Under other circumstances, changes in season cause species to associate with different microhabitats throughout the year. Behaviours such as this indicate that there is a complex interaction between internal and external climate, and subterranean invertebrates (Mammola, Piano & Isaia, 2016; Lunghi, Manenti & Ficetola, 2017). Other interactions observed in a cave have been on a biological level, spiders and moths cohabit several caves, however as they are predator and prey respectively this cohabitation is at a distance. A combination of microclimatic variables and predator-prey interactions combine to dictate the position of both these species within certain caves (Manenti, Lunghi & Ficetola, 2015; Mammola & Isaia, 2016).

2.3.2.3 Grike biodiversity and Microclimate

The grike microclimates likeness to a forest floor has been a feature of studies of both microclimate and biodiversity in the grike. The comparison to a forest floor is reinforced by Ward and Evans' study of grike flora (1975). This study found that many of the most common plants found in grikes were also native to forest surroundings including Dogs Mercury (*Mercurialis perennis*), Wood Violet (*Viola riviniana*), Herb Robert (*Geranium robertianum*), Hart's Tongue Fern (*Asplenium scolopendrium*) and a large number of other shade-tolerant ferns.

Although grikes and forest floors are similar in some respects, later investigation identified that the microclimate was different in some respects, reporting that several plant species show a preference for specific grike ranges (Dickinson, Pearson and Webb, 1964). Some examples are illustrated in Table 2.2.

Table 2.2 Floral species ranges within a grike (Dickinson, Pearson and Webb, 1964).

	Below 55cm	Above 55cm
Grikes surveyed	57	43
Geranium sanguineum	15	1
Geranium robertianum	29	11
Thymus drucei	18	2
Teucrium scorodonia	24	7
Molinia caerulea	16	0
Sesleria caerulea	36	5
Festuca ovina	18	2

Jonathan Silvertown's (1983) later work on limestone pavement plant species refined prior work by providing species ranges. Survival of plant species at different depths was attributed to the increased protection from grazing and more stable environmental conditions as depth increases.

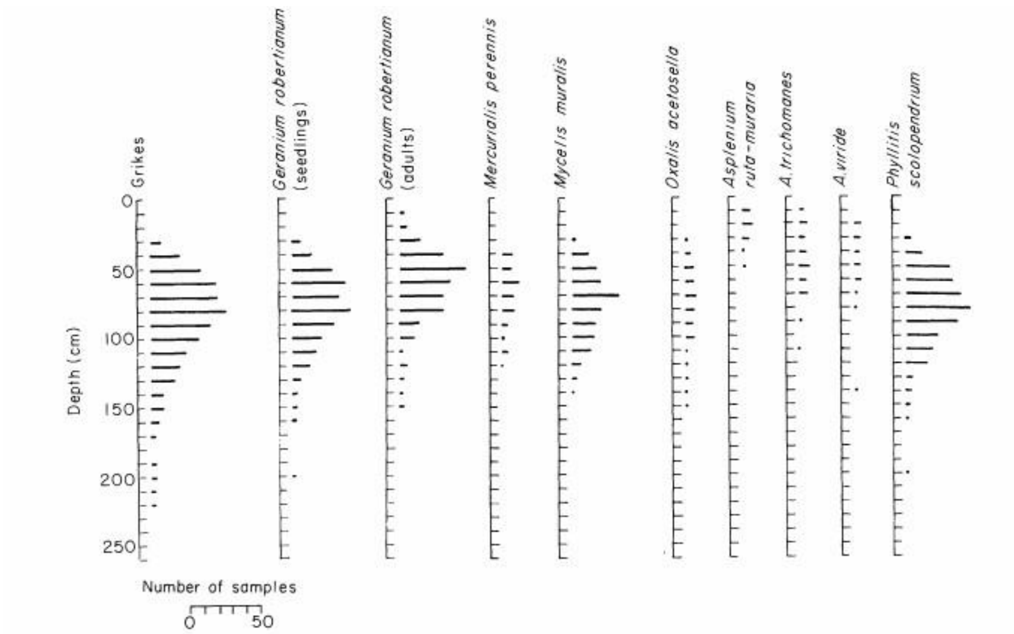


Figure 2.13 Prevalence of Flora at different depths within limestone pavement grikes (Silvertown, 1983).

Despite the similarities to a forest floor, the grike habitat is a unique entity. Ward and Evans (1975) found that the limestone of the grikes was attracting cliff and scree species such as Maidenhair Spleenwort (*Asplenium trichomanes*) and Wall Rue (*Asplenium ruta-muraria*). More recently floral species distribution has been analysed in relation to the orientation of grike. This found that the NS orientated grikes have a greater diversity when compared to EW grikes (Inman, 2000; Lloyd-Jones, 2001). Compared to investigations of plant life in limestone pavement grikes, there are fewer documented cases of investigations examining invertebrate life with regard to the grike microclimate. The most notable is Willis (2011), who created the holistic system of limestone pavement classification detailed in the site selection rationale in Chapter Three. As part of testing the classification of limestone pavements, Willis compared mollusc species abundance to several limestone pavement variables including grike depth. Other studies relating to grike microclimate and invertebrates have shown that snails were sensitive to grike orientation during winter, woodlice are more likely to be found in grikes closer to the centre of the pavement, and upper areas of the grike provide wind channels and a valuable structural element for the web-building spider *Araneus diadematus* (Colebourn, 1974; Webb & Gladding, 1998; Sheehy, 2004; Swindale, 2005; Willis, 2011). Leaf litter is blown from the surface of the clints and settles in grikes (Burek & Legg, 1999). Air movement transports these leaves, and the lack of strong wind in the grikes ensures they are not transported elsewhere. The detritus collected is of great importance to the invertebrates which live in the grikes (York, 2009). The various species of Isopoda present in the grike rely upon a fresh source of leaf litter and respond negatively to leaf litter of low quality (David & Gillon, 2009, York, 2009).

2.3.3 Other influences on Biodiversity

<u>2.3.3.1 Soils</u>

There are several soils associated with limestone pavements that materially influence the biodiversity of the habitat (Carroll, 1986; Burek, 1998; Conway, 2007). As previously discussed, limestone is soluble when exposed to acids in rainwater. The non-soluble residual remnants of the now largely decalcified limestone go on to form soils which are known as rendzinas (Ryan, 1963). As such, these soils are found only where the limestone has a sufficiently strong influence (Ryan, 1963) such as The Burren in Ireland (Jeličić and O'Connell, 1992). The formation of rendzina soils is atypical in the climate of the UK and Ireland, as it occurs only in humid environments such as those found in a grike (Carroll, 2012). Rendzinas are a rarity in Britain and are protected as part of BAP priority habitats (JNCC, 2007). Despite the origins of these soils, the rendzinas are largely decalcified to the extent that there are no longer free carbonates in their profile, yet they retain a relatively high pH (Ryan, 1963). These soils are free-draining, have a relatively high organic content for mineral soil and are a good substrate for plants (Ryan, 1963). The plant communities found on rendzina are largely determined by their tolerance for this high pH (Moles, Hayes, O'Regan & Moles, 2003).

Other soils associated with limestone pavements derive from the soils which previously covered the pavement (Sweeting, 1966). These sediments are largely associated with deposits left by glaciers in the form of till. These deposits can be highly varied, producing a range of depths of sediment and a variety of organic matter content, particle-size, acidity, clay content and geochemistry. Although much of the glacial till can be traced to local sources (Carroll, 1986), analysis has identified the source of other materials are from further afield, having been carried by the movement of ice from their place of origin (Burek & Cubitt, 1991). Such is the diversity of glacial tills found on limestone pavements of the Yorkshire Dales National Park that it this is a major determinant of the diversity in flora between pavements (Thom, 2003). Likewise, evidence of glacial deposits in The Burren, show a varied provenance for soil parent materials which contribute to the exceptionally high biodiversity found there (Moles & Moles, 2002).

Soils have been hypothesised to underpin the biodiversity of limestone pavements on several sites directly (Willis, Burek & Alexander, 2009). On the pavements of Morecambe Bay, a correlation has been observed between the presence of Heather (*Calluna vulgaris*) and Bracken (*Pteridium aquilinum*) and areas of loess sediments (Vincent & Lee, 1981). Willis (2011) identified that sward height in grasses had a significantly negative relationship with soil depth in grikes, which was identified as a surrogate measure to indicate high grazing pressure. In southern Ontario in Canada species, richness correlated with mean soil depth and soil depth heterogeneity (Lundholm & Larson, 2003; Lundholm, 2010; Richardson et al., 2012). In Perthshire, the rendzinas within grikes derived from Dalradian limestone have a noted association with Meadow Oat-grass (*Polygono-Helictotrichetum pratensi*) (Gauld, 1985).

<u>2.3.3.2 Land use</u>

On The Burren, there is evidence to show that human influences such as fire and grazing of livestock are partly responsible for the characteristically open limestone pavements valued today (Lucey, 2001). Despite their wild and barren appearance, many limestone pavements in Britain and Ireland are managed through grazing. Silvertown observed the selective pressures of grazing on limestone pavement biodiversity through observations of the varied sensitivity to grazing pressures by different grike species (Silvertown, 1982). Grazing can be undertaken by several different animals and is a necessary part of the management of limestone pavements and their associated grassland (Deenihan, Donlan, Breen & Moles, 2009). Both overgrazing and undergrazing on The Burren have been observed to result in a reduction of grassland biodiversity (Moles & Breen, 1991; Moles, Breen & O'Regan, 2005). Undergrazing has been observed to favour blue-moor grass (*Sesleria caerulea*), fescues and some particularly competitive herb species which eventually become dominant and out-compete weaker native flora such as quaking-grass (*Briza media*) and hair-grass (*Koeleria macrantha*) (Dunford, 2002; Moles, Breen & O'Regan, 2005). In more extreme cases undergrazing can allow scrub communities made up of Common juniper (*Juniperus communis*), Blackthorn (*Prunus spinosa*), and Bramble (*Rubus fruticosus*) to encroach the grassland and spread to limestone pavements (Deenihan, Donlan, Breen & Moles, 2009; Cross, 2006).

The effects of overgrazing are detrimental to biodiversity (Thom et al., 2003). Pavements experiencing overgrazing exhibit lower occurrence of species with high conservation value, dwarf growth of trees and excessive use of grikes by grazing rabbits results in soil enrichment from droppings leading to species classified as "less favourable" by Willis (2001) such as nettles (*Urtica dioica*). Overgrazing also has the detrimental effect of increasing downslope mass movement rates of decalcified soil from upper slopes resulting in a change to soil texture and composition (Moles, Hayes, O'Regan & Moles, 2003) which as previously discussed will inform the biodiversity using the substrate.

In order to manage these effects, The BurrenLIFE project has sought to strike a balance between under and overgrazing by promoting a "grazing days" system based on one grazing day equalling one livestock unit/day. The system described has allowed a quantification of the amount of grazing any one site receives and for land managers to recommend the optimal number and timing of grazing days per site (Williams, 2009).

As mentioned previously, the type of animal grazing the limestone pavement also has an impact on the biodiversity. Sheep have historically been the primary grazer of The Burren and areas of limestone pavement in Britain such as North Yorkshire and the Lake District (Miller, 1976; Dunford, 2001; Pears, 2014). More recently, cattle have increased in frequency on The Burren (Dunford, 2002). Sheep are linked with considerable grazing damage to limestone pavements (Burek, 1999). Sheep damage is in part due to their method of cropping, as they both defoliate and uproot plants as well as trampling and burying seedlings (Miller, 1999). Despite the damage which is caused by mismanagement, these same tendencies may be harnessed to create bare land for seed colonisation if grazing takes place between late August and early September (English Nature, 2004). Although not a commercial grazer of grasslands and limestone pavements by extension, rabbits are a near-ubiquitous part of the arable countryside of Britain and Ireland (Webb & Glading, 1998). The effects of one rabbit grazing are estimated to be one-tenth of that of a single sheep (Dunford, 2001); however, the appearance of one rabbit above ground is estimated to indicate ten more below ground (Thom et al., 2003). The impact of rabbit grazing on limestone pavements are hypothesised to be closely linked to the width of grikes, as rabbits are less able to graze from the clint and need to enter into a wider grike to graze from the bottom (Brandes, 2000). The impacts of rabbit droppings previously discussed and their contribution to overgrazing by close cropping are detrimental to biodiversity and the species of conservation importance (Dunford, 2001; Thom et al., 2003; Willis, 2011). Unlike sheep or cows, grazing rabbits cannot be strategically timed to effect positive impacts. It is, therefore, only possible to control and monitor the rabbit population (Thom, 2009).

Cattle are the second most plentiful commercial grazers of limestone pavements of England (Miller, 1976) and a frequent grazer on The Burren (Dunford, 2002). Cattle graze differently to sheep and rabbits, as they do not graze selectively, do not target flower heads and pull vegetation out of the ground rather can close cropping which leaves the bare ground for recolonisation (Dunford, 2001; Natural England, 2014). Cattle also are capable of creating access to rougher areas by trampling through the scrub, while there is anecdotal evidence that GPS tracked cattle avoid straying onto clints (Bevan & Hibbins, 2008; Natural England, 2014). This combination of factors makes cattle the most appropriate grazers for limestone pavements (Graham, Tim & Paul, 2007; Milligan, 2003).

Feral goats are notable grazers of limestone pavements on The Burren and the Great Orme in North Wales (Dunford, 2001). As grazers goats tend to be generalists, preferring the most palatable vegetation available, but will also eat less palatable scrub when preferred plants are dormant (Valentine, 1990; Bullock & O'Donovan, 1995). Goats appear to be valuable grazers for the management of scrub; however, different breeds goat have different grazing habits, and in order to be effective as a scrub management measure their application needs to be carefully monitored (Deenihan, Donlan, Breen & Moles, 2009; BurrenLIFE, 2010).

2.3.3.3 Climate

The macroclimate of Britain and Ireland exists within the maritime sub-classification of the Earth's temperate zone. This zone is characterised by westerly winds, steady temperatures across seasons and possessing fewer of the extremes observed elsewhere in the Earth (Barrow & Hulme, 2014). Further specific information on the macroclimate of the areas of Britain and Ireland studied as part of this research is found in Subsection 3.3.4 of the methodology chapter. The macroclimate's more direct effect on biodiversity in a grike can be observed through the impacts climate has on microclimate. As has been discussed previously, the grike is hypothesised to create a microclimate which is more thermally stable, higher in relative humidity and receives lower light intensity than the external climate. This microclimate is however intrinsically linked to the external climate as the surface temperature informs that of the grike and produces the same diurnal cycles which continue to inform the grike microclimate (Dickinson, Pearson and Webb, 1964; Silvertown, 1982; Alexander, Burek & Gibbs, 2007). In Willis' (2011) thesis, it was discovered that climatic influences such as wind-speed, number of frost days and precipitation were strongly related to biodiversity. Specifically, it was found that wind-speed influenced the height of emergent species, suggesting that exposure influenced plant communities on high altitude and coastal pavements. In the Republic of Ireland, the wind is described as one of the most critical elements shaping The Burren vegetation (Nelson, 1985). Winter on the west coast of Ireland has been described as a “succession of westerly gales with westerly winds between” (Praeger, 1934). The influence of the wind is most intense for large swaths of The Burren limestone pavements found on the coast (Walsh, 2012). These different effects impact biotic life differently based upon their ecological niche (discussed in Chapter Seven) and the climate of the site (discussed in Chapter Three).

2.4 Protection, threats and management

2.4.1 Conservation status

In a 1976 survey, only 2600 hectares of pavement were identified in the UK, of which 97% had suffered damage in one form or another (Ward & Evans, 1976, Webb & Gladding 1998, Pendry & Allen, 1999). Between 1994 and 2006 the conservation status of UK limestone pavements was assessed in the UK finding that 82% of the total limestone pavement coverage was in “Unfavourable” condition, however, this condition was considered stable (Joint Nature Conservation Committee, 2007). A reassessment of the condition of pavements between 2007 and 2012 provided the conclusion that at least 49% of the UK habitat area was in “Unfavourable” condition (Joint Nature Conservation Committee, 2013). A 2009 assessment of the limestone pavements in the Republic of Ireland found that three of the six pavements assessed were “Favourable”, two were “Unfavourable/ Inadequate”, and one was “Unfavourable” (Murphy & Fernandez, 2009). Summarised conclusions of these reports are provided by the European Union which classes limestone pavements in the UK to be “Unfavourable/Bad” defining this to be “in serious danger of disappearing (at least regionally)”. Limestone pavements are classed as “Unfavourable/Inadequate” in the Republic of Ireland and described to be “in a situation where a change in management or policy is required to return the habitat to “Favourable” status, but there is no danger of disappearance in the foreseeable future” (European Environment Agency, 2013).

2.4.2 Protection

Since 1981 limestone pavements have been protected under the UK and European law (Wildlife & Countryside Act, 1981 and EEC Council Directive 92/ 43/EEC, Bell & McGillivary, 2000). This protection made it an offence to remove or disturb the limestone from a pavement. These orders have, however, been criticised for the loose definition used to describe limestone pavements in law, the right of landowners to object to orders on their property and the recurrent problem of poorly defined boundaries which may lead to limestone pavement land not to be included within the order (Webb, 1995). In line with this protection certain limestone pavements have been designated as Special Areas of Conservation and given enhanced protection to prevent damaging activities (Joint Nature Conservation Committee, 2014; National Parks & Wildlife Service, 2019). These sites have been chosen to reflect the special responsibility for this priority habitat type, and are typically larger sites but also account for geographic variation, level of grazing, pavement type and presence of rare species. There are eleven such Special Area of Conservation (SAC) sites in Britain and twenty-four in the Republic of Ireland (National Parks & Wildlife Service, 2019; Joint Nature Conservation Committee, 2019). Many other sites in the UK are also Sites of Special Scientific Interest (SSSI), and it is estimated that around 60% of limestone pavements gain further protection from this designation including Ingleborough Karst, Malham Cove, Hutton Roof, and Gait Barrows (Denbighshire Countryside Service, 2007; Willis, 2011).

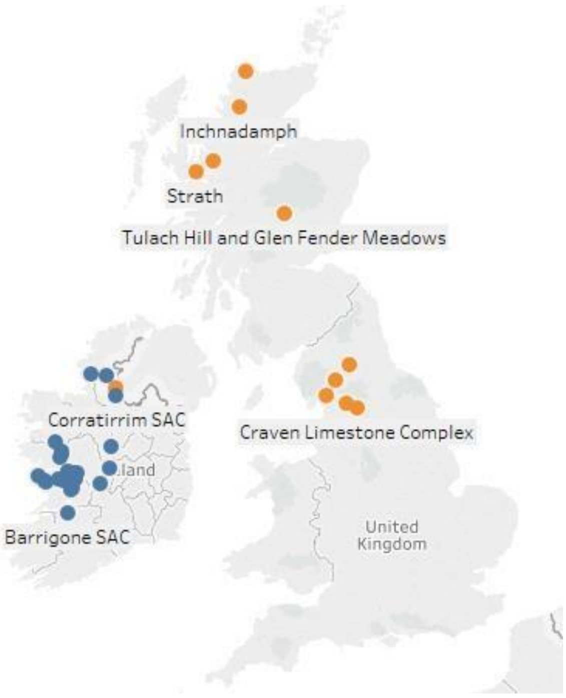


Figure 2.14 SAC site locations in Britain and Ireland (Orange) UK sites (Blue) Republic of Ireland (National Parks & Wildlife Service, 2019; Joint Nature Conservation Committee, 2019).

Such importance has been placed on our responsibility to protect this habitat, that limestone pavements remain the only natural habitat protected by UK criminal law (Rodgers, 2013).

The mechanism for this protection is the “Limestone Pavement Order” (LPO) originally placed upon limestone pavements in England, Wales and Scotland as part of the Wildlife and countryside act 1981. This protection was revoked in Scotland in 2004 (Rodgers, 2013) and no limestone pavements in Wales have been proposed for protection as it was stated in the House of Commons that “the sites are

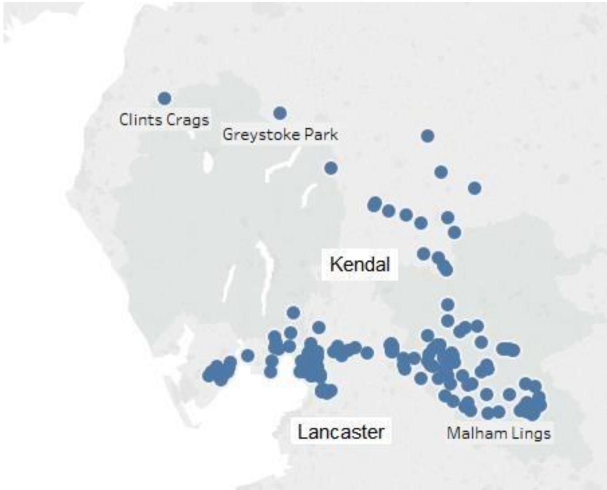


Figure 2.15 Limestone Pavement Order locations (data.gov, 2019)

relatively small and not under threat" (House of Commons, 1992). As a result, only the limestone pavements in the Northwest of England are protected under Criminal Law. Since the implementation of LPOs, pavement extraction has been virtually eliminated in England (Webb & Glading, 1998).

In addition to national legal protection, some limestone pavements have been designated as Regionally Important Geodiversity Sites (RIGS). Although this designation holds no legal protection, local authorities increasingly recognise the RIGS status through planning guidance (Gray, 2013).

Areas of The Burren and the Isle of Anglesey in Wales have also been designated as United Nations Educational, Scientific and Cultural Organization (UNESCO) Global Geoparks. Global Geoparks are internationally recognised sites of geological significance, which are managed with a holistic ideal of protection, education and sustainable development (UNESCO, 1999). The Geopark title is not a legislative designation but stipulates that a site must be protected under appropriate legislation (UNESCO, 1999).

Despite protection in Great Britain and Ireland, these geodiversity features continue to be under threat from damage and development (Mauerhofer, 2015). Margules, Nicholls and Usher (1994) and Thom et al. (2003) provided proof of this degradation, by each repeating aspects of Ward and Evans (1975) floristic surveys. In 1994 it was found that more species were lost than gained and by 2003 there had been a 33% decline in high-quality pavements and that 92% of pavements could be classified as "Unfavourable" in condition (Margules, Nicholls & Usher, 1994; Thom et al., 2003). It has also been reported that grasslands and pavements with high biodiversity, despite designation under the European Union (EU) Habitats Directive as a priority habitat, are gradually being supplanted by grassland, scrub and woodland with poorer biodiversity (Dunford, 2002).

2.4.3 Non- climate Threats and current management

2.4.3.1 Scrub

Scrub encroachment is an increasingly important issue for limestone pavement management in the whole of Britain and Ireland. A lack of grazing or unsympathetic land management combined with a decline in traditional scrub management through coppicing has led to an overgrowth of scrub species as discussed previously in this chapter when exploring undergrazing (Dunford, 2001; Dunford, 2002; Deenihan, Donlan, Breen & Moles, 2009). In order to manage this issue, some countries have been forced to undertake costly restoration schemes using large machinery or intensive multi-person teams which may be limited in their effectiveness and prove cost-prohibitive in the long term (Dunord, 2002). Reinstating coppicing may be preferable compared to the cost of intensive scrub removal to prevent scrub encroachment, as was carried out by the Morecambe Bay LIFE Project (Milligan, 2003). It is, however, more common to use more strategically effective grazing practices to manage scrub as was achieved by The BurrenLIFE project described previously, where stock timing and application were managed through grazing units. Paradoxically, management guidance for upland areas of limestone pavement suggests scrub enhancement through direct replanting of scrub and protection from grazing, as these features provide a valued contribution to habitat diversity (Joint Nature Conservation Committee, 2009; Blakesley & Buckley, 2016). Both scrub removal, management and enhancement all seek to achieve a balance to "protect" the character of limestone pavement whilst providing a structural variety of interest to invertebrates (Joint Nature Conservation Committee, 2009).

2.4.3.2 Other "undesirable" species

Management recommendations taken from over a decade apart highlight the immediate threat of overgrazing and recommend limiting rabbits' access to the limestone pavement flora (Webb & Gladding, 1998; Willis, 2011). The presence of this species correlates negatively with floral quality (Burek & Legg, 1999a; Conway & Onslow, 1999) because of the disturbance they cause in addition to indiscriminate grazing (Webb & Glading, 1998; Miller, Geddes and Mardon; 1999). Further management recommendations include control of "undesirable" species such as shrubs on open pavements (Webb & Glading, 1998) and bracken, cotoneaster species and Non-Native Tree Species (Willis, 2011).

2.4.3.3 Damaging human activity

The human impacts which threaten limestone pavements are both direct and indirect. The most notable indirect threats are unsympathetic grazing practices which have been discussed previously concerning land use, and the threat of climate change that deserves a separate subsection to be discussed later. The direct threats of human action on limestone pavement have been well documented by Goldie (1976; 1986; 1993). Historically quarrying of limestone from pavements, and incidental damage around mineral workings and kilns make up some of the major reasons damage has taken place in Britain. In The Burren, rocks from limestone pavements would have been mined by hand to build tombs, forts, walls and roadways (Dunford, 2002). This activity is not limited to the past as Sweeting (1966) relates that in England organised businesses took advantage of the surface availability of shaped limestone and that farmers encouraged such action to extend the potential grazing area available. The scale of this removal is exemplified in one discussion from the House of Commons which relates the removal of 1,000 tonnes of limestone from Winskill Stones, north of Settle for rockery gardens (House of Lords, 1995). On The Burren, state-subsidised “reclamation” of limestone areas took place during the 1980s resulting in 1371ha of extensive damage through mechanical pavement removal (Drew & Magee, 1994). Even more recently, the demand for water-worn limestone in the construction and horticultural industries has continued the removal of clints from The Burren (Pendry & Allen, 1999; Dunford, 2002).

In England, there is also evidence of damage from mismanagement where commercial planting of non-native tree species has taken place on limestone pavements and their surrounds (Milligan, 2003). Likewise, in England, physical threats such as dumping of manure and lighting bonfires on pavements have been recorded alongside indirect actions such as incidental drift of pesticide and fertiliser impacting the flora of pavements (Spiteri, 1991). Despite these incidents, the protection afforded to limestone pavements in England has largely eliminated the issue of clint removal (Webb & Glading, 1998).

A more recent threat to the health of the more popular limestone pavements is that of tourism on an industrial scale. In 2014 there were an estimated 571,000 coach trip visitors to The Burren (Saunders, 2015). While all tourists do not cause damage, damage to limestone pavements does occur as a result of visitor activity. On The Burren damage is caused by the removal of rock, toppling erratics, malicious destruction and construction of mini-dolmens emulating the megalithic tombs found in the area (Dunford, 2002). In England and Wales, tourism to limestone pavements is not as common. Here there is evidence to suggest that the amount of stone removed from individual limestone pavements correlates with the accessibility of a site and more popular pavements showed greater levels of litter. However, there was no evidence to suggest that high visitor numbers detrimentally affected the flora or pavement integrity (Willis, 2011). Projects such as GeoparkLIFE on The Burren worked with stakeholders to introduce a code of practice for sustainable tourism, trained business in sustainable practices and instituted a practice of monitoring in order to reduce the impact of tourism (Burren and Cliffs of Moher: GeoPark, 2017).

2.4.4 Climate Threats and management recommendations

There is a wide consensus that climate change is impacting the natural world in adverse ways and climate change is considered a major threat to the future condition of the limestone pavement habitat in the long term (Joint Nature Conservation Committee, 2007). For this reason, this study takes the view that if the ecology of the limestone pavement is observed to be at risk of climate influenced negative change; it is potentially damaging to do nothing. Action taken must also be reasoned and appropriate in scale because the unforeseen consequences of human interference can have adverse effects on species and habitats (McLachlan, Hellmann & Schwartz, 2007).

2.4.4.1 Climate change and Britain and Ireland

The atmosphere surrounding the Earth is typically made up of large concentrations of nitrogen (78%) and oxygen (21%) and only trace amounts of carbon dioxide (CO_2) (0.039%) and methane (CH_4)(0.00017%) (Barry & Hall-McKim, 2014).Concentrations in atmospheric greenhouse gases such as CO_2 and CH_4 have continued to increase since the European industrial revolution began to accelerate fossil fuel consumption (Pachauri et al., 2014). Toward the turn of the century, Swedish scientist Svante Arrhenius first proposed that CO_2 may cause a warming effect on the surface of the Earth (Fleming, 2005). Since this time observations were taken from global mean surface temperatures, melting of sea-ice, accumulation of heat in the upper oceans and rising sea levels indicating that emissions-driven anthropogenic climate change is occurring on a global scale (Pachauri et al., 2014). These observations have shown the wide-ranging impact of climate change on the Earth and its systems. The prospect of unalterable climate change spurred climatologists to document the progress of observed climate changes and gauge future impacts that changes may have. Management of habitats for the future is a challenging task, as the processes involved in climate change are chaotic (Lorenz, 1967) and their exact state cannot be predicted years in advance. However, different scenarios can be modelled by isolating statistically significant climate variables and hypothesising these variables long-term effects on climate, under specific assumptions and tolerances (Palmer, 2017).

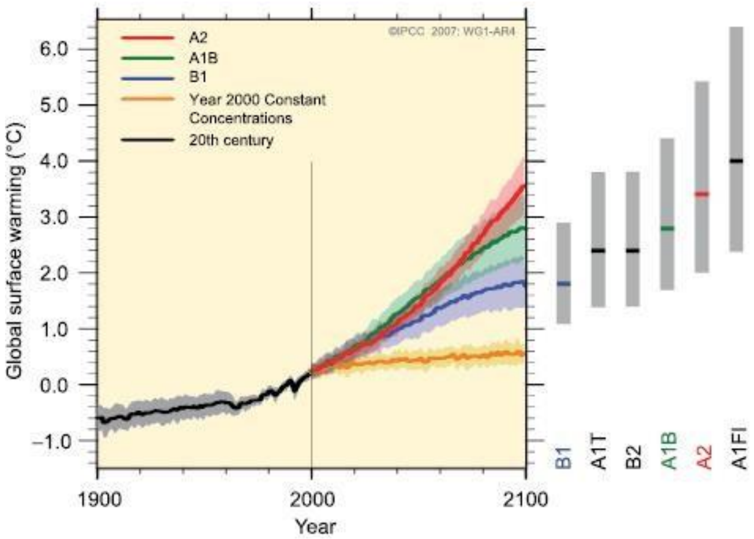
The most credible climate projections are those given by the Intergovernmental Panel on Climate Change (IPCC). This intergovernmental body draws together the peer-reviewed literature on the topic of climate change and periodically publishes reports which have the agreement of leading climate scientists and the consensus of participating governments. The projections made by the IPCC do however contain uncertainties in the physical science underpinning the models and ambiguities in the socio-economic scenarios that for the basis of the projections (McMahon, Stauffacher & Knutti, 2015).

The latest of these reports was published in 2014 and stated that anthropogenic emissions of greenhouse gases have increased since the start of the industrial era. These emissions have led to concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in human history. These exceptional circumstances are “extremely likely to have been the dominant cause of the observed warming since the mid-20th century” (Pachauri et al., 2014).

Anthropogenic emissions have led to the following key issues for the limestone pavement habitat; however, these are only a limited few threats among many that will affect habitats and humans globally.

- There has been a linear trend toward global warming by a magnitude of 0.85°C [0.65°C to 1.06°C] over the period 1880 to 2012.
- Globally the number of extreme weather events is increasing in frequency.
- Northern Hemisphere precipitation over both land and sea has increased since 1901, and the number of high precipitation events will increase compared to drought events.
- From 1901 to 2010, the global sea level rose by 0.19 [0.17 to 0.21] m and continues to rise at an increasing rate resulting in coastal habitat loss.
- There are multitudinous further impacts of climate change, including effects on water resource quality, snowmelt rate and influences on species.
- The projected increase in global mean surface temperature by the end of the 21st century is dependent on the action which is taken now. (Figure 2.16)

(Pachauri et al., 2014).



A1 = population peaks mid-century, and converges in urban centres around a diverse advanced technology. A1FI = A1 + Fossil-fuel intensive, A1T = A1 + non-fossil fuel & A1B = A1 + Balance of Fossil fuel and renewable. A2 = population continually increases, is self-reliant, fragmented and preserves local identities
B1 = population peaks mid-century, material interest reduces and clean, and resource-efficient technologies emerge.
B2 = continuous low rate of population increase, less diverse green technology, a fragmented society focused on environmental protection.

Figure 2.16 Graphical representation of the climate change scenarios projected by the IPCC.
(Pachauri et al., 2014)

Using the IPCC projections, the Environmental Protection Agency (EPA) has assessed the key impacts which are likely to affect the Republic of Ireland. These warn that coastal areas, including a large area of The Burren, could experience coastal flooding and erosion. Flooding will inundate coastal areas due to higher than normal tides, surges and wave-overtopping, combined with fewer storms with greater intensity (Desmond, O'Brien & McGovern, 2007). Changes in temperature in the Republic of Ireland are based on the four RCP emission scenarios. The RCP scenarios or the Representative Concentration Pathways refer to a change in the balance between incoming and outgoing atmospheric radiation caused primarily by changes in atmospheric composition. A higher RCP value indicates a balance toward higher incoming radiation such that RCP values are commonly labelled in the following way, RCP2.6 (low), RCP4.5 (medium-low), RCP6.0 (medium-high) and RCP8.5 (high) (Met Éireann, 2017). Figure 2.17 shows the projected temperature anomaly for Ireland for the years 2035-2060 for the RCP4.5 and RCP8.5 emission scenarios.

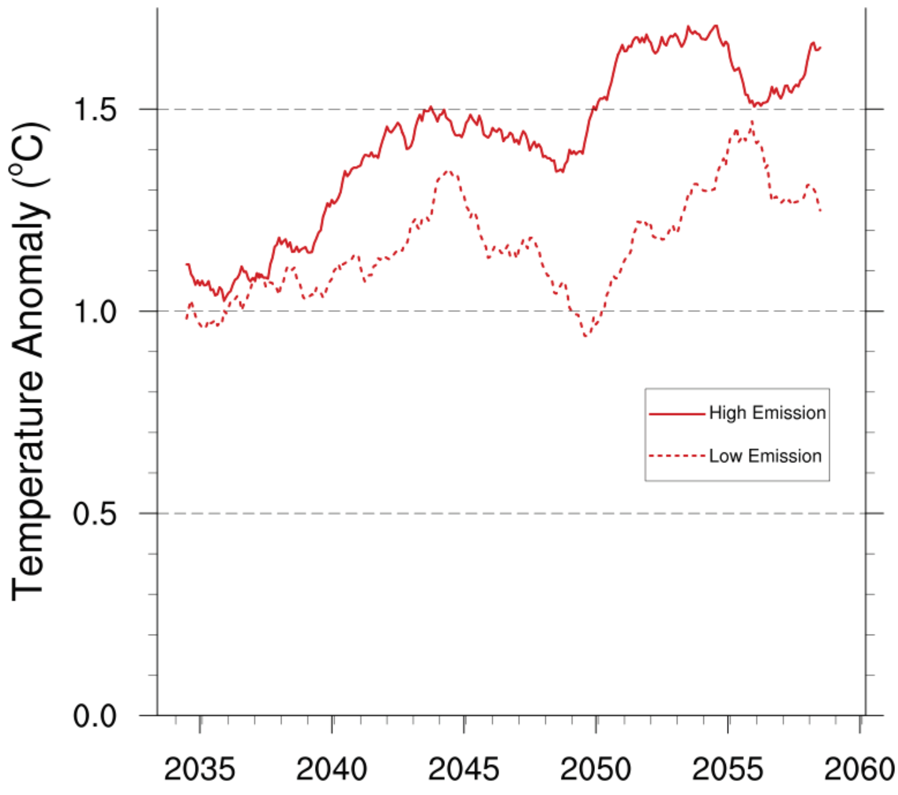


Figure 2.17 Ensemble mean of average monthly temperature anomaly for Ireland for the years 2035-2060 for the RCP4.5 and RCP8.5 emission scenarios (Nolan, 2013).

The projections generated by the IPCC are global and do not deal with a high resolution of local variations. Despite issuing maps of the globe that illustrate the most and least affected ranges, the size of the affected areas is very large, masking much of the variation experienced in reality due to the local climate. To predict climate change on a local level is often extremely difficult, and the reduction of spatial scale increases the uncertainty of the outcome (Jenkins et al., 2009).

In the UK attempts have been made by The Department for Environment, Food and Rural Affairs (DEFRA) and over 30 other organisations to refine and tailor climate projections from the IPCC to specifically address the issues Great Britain will face over the coming years (Murphy et al., 2018). UKCP18 is the name given to the latest projections issued by DEFRA. The UKCP18 projections over land and marine areas are produced for the same four different emission scenarios as the IPCC. The probabilities of each scenario occurring cannot reliably be estimated (Murphy et al., 2018).

These projections have been used to propose a number of possible scenarios in Great Britain.

- Sea level will continue to rise around Britain and Ireland accompanied by changes in tidal and wave characteristics.
- Average projected precipitation will change by -1% to +35% by the 2070s in winter and by -47% to +2% in summer.
- Significant increases in temperature will occur during both winter and summer (Murphy et al., 2018)

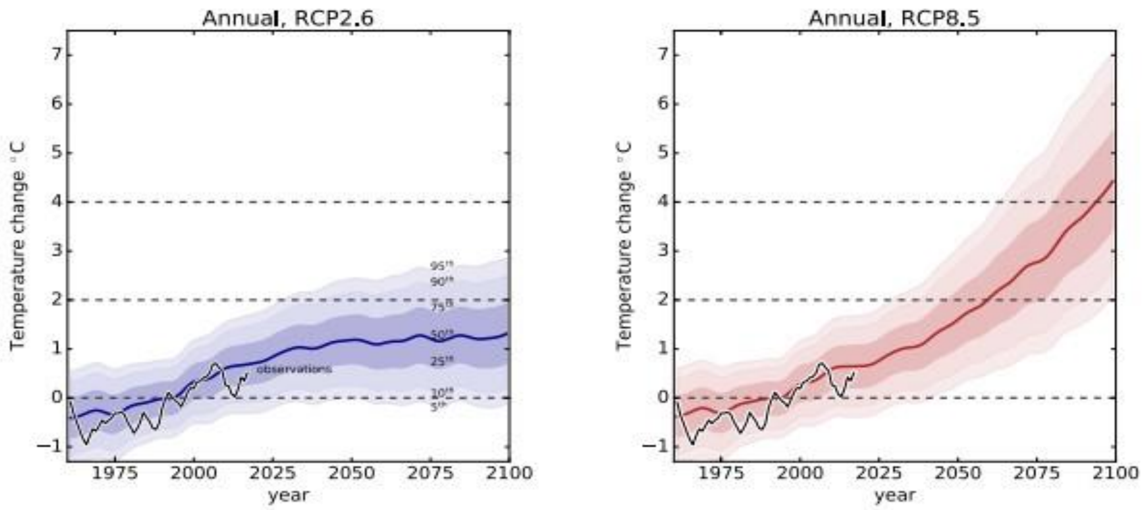


Figure 2.18 UK temperature differences from 1981-2000 average (Murphy et al., 2018).

2.4.4.2 Uncertainty in the effects of climate change on biodiversity

When creating an understanding of the influence of climate change on biodiversity trends, biodiversity models are initially created using current climatic conditions. These models are then used to project future patterns in biodiversity based on climate projections from organisations such as the IPCC. As previously described, there is a level of uncertainty inherent in these projections (McMahon, Stauffacher & Knutti, 2015). Furthermore, the emissions scenarios employed, the assumptions used in modelling carbon cycle feedbacks and downscaling of projections create additional avenues with varied climate outcomes (Jenkins et al., 2009, Pachauri et al., 2014; Murphy et al., 2018). The variability created by different projections has encouraged researchers to use numerous projections from a range of sources when creating biodiversity models (Araújo & New, 2007).

With regard to the models used for understanding the biodiversity, greater complexity is introduced as biodiversity models also inherently produce further considerable variability (Thuiller et al., 2019). There are several species distribution models used in practice, each of which has strengths and weaknesses, depending on their application (Pacifici et al., 2015). The structural decisions made during the model's creation and knowledge of the ecological system being modelled can have large impacts on the model's accuracy (Zurell et al., 2016). An oversight in almost all studies of the impacts of climate change on species is the focus on only the direct impacts of climate change (Pacifici et al., 2015). Indirect impacts from within biological communities and from human resource changes are likely to have more complex and damaging consequences (Pacifici et al., 2015).

When the uncertainties in understanding the impacts of change on the climate and biodiversity are taken together, it is understandable that there is debate as to the probable effects of climate change on habitats (Guisan & Thuiller, 2005).

2.4.4.3 Macro climatic effects of climate change on biodiversity and distribution

There is scarce research on the direct effects of climate change on flora and fauna found within the limestone pavements themselves, and as previously discussed there is a large amount of uncertainty when dealing with specific outcomes of climate change for species distribution. Generalised predictions of the effects of climate change may point toward some probable impacts on grassland species which inhabit shallower grikes. Some species appear to thrive under an increase in temperature, but over winter water availability appears to be a limiting factor (Masters, 1998; Sternberg, 1999; Phillips, 2018; Basto et al., 2018).

Future climates are predicted to have greater variability and more frequent extreme events (Murphy, 2018). These are currently poorly understood when compared to shifts in means; however, these will likely have greater effects on ecological systems (Foden, 2019). Extreme events which may affect limestone pavements may include extremes of heat and cold; however, due to their more stable microclimate, it is more likely that flooding may be a more pressing risk. Sea level in regions of the west coasts of Ireland and the UK in which limestone pavements are found is estimated to rise by between 0.3m and 0.65m by the end of the century (Met Office, 2018). A rise of this degree would not affect most limestone pavements; however, those on the far west coast of the Republic of Ireland such as Polsallagh will expect to experience some submersion. Storm surges may impact other coastal limestone pavements on the west coast of Great Britain which may experience saline incursion, impacting the soil chemistry and by extension impacting the species able to grow under such conditions (Prosser et al., 2010; Hoggart et al., 2014). Further flooding may be experienced inland, as rivers and turloughs experience swelling from the large quantities of rain expected under many predictions (Viles, 2003). Risk areas for flooding around turloughs on The Burren include several areas which contain limestone pavements near to the town of Gort (Naughton, Johnston, McCormack & Gill, 2017).

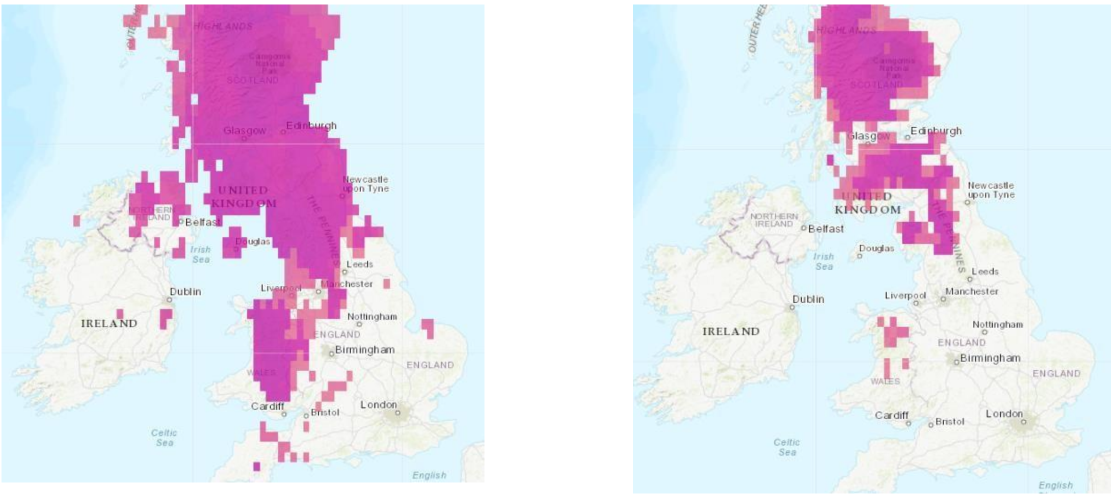
The impacts of climate change described above do not act in isolation of other threats to the wellbeing of habitats. The threats posed by more hostile conditions increase the susceptibility of species to disturbance from non-climate threats, changes to interspecific interactions and change in phenology (Ackerly et al., 2010). Many of these threats have a greater impact on populations than direct abiotic impacts of climate change, and this is even more apparent for species in higher trophic levels (Ockendon et al., 2014).

If the climate were to become warmer within their current geographic range, species might be forced to move to a more hospitable region. Migration such as this often means that more northern latitudes or a higher elevation are sought under most climate change scenarios (Thomas et al., 2011). For a generalist species found at a lower altitude or in the south of Britain or Ireland, this may mean that their range moves or expands. More specialised species found at high altitude or northern latitude, may not find hospitable habitats, resulting in local extinction.

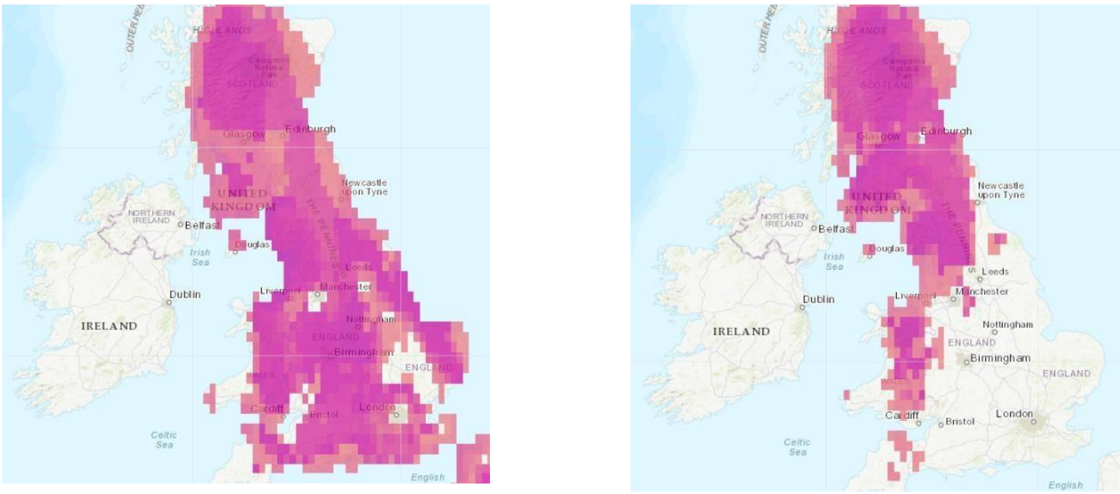
Despite the uncertainty surrounding species distribution models, there is a demand for them to help understand how species distributions will change in the future (Thuiller et al., 2019). The Wallace initiative has been developed by James Cook University and the University of East Anglia. This initiative provides bespoke species distribution models for approximately 135,000 terrestrial species using outputs from 21 climate models to produce a range of likely distribution changes to manage uncertainty (Price et al., 2018). Figure 2.19shows the changes in the range projected under a 2°C rise in temperature for three limestone pavement species considered Nationally Scarce in Britain from species distribution models generated by the Wallace Initiative. A 2°C rise in temperature is a modest rise; however, a rise of 3.5°C and a more dramatic change to species ranges is equally possible by the end of the century (Murphy et al., 2018).

Baseline 2°C rise in temperature

Downy red currant (Ribes spicatum)



Baneberry (Actea spicata)



Fingered sedge (Carex digitate)

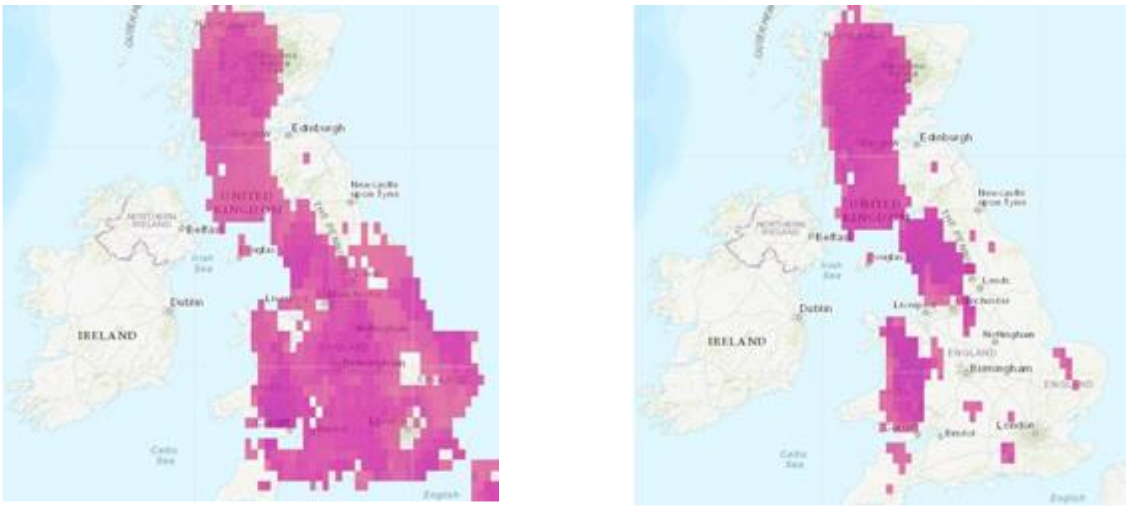


Figure 2.19 50th percentile or "best estimate" change in species distribution from baseline to a 2°C temperature increase (Price et al., 2018).

The microclimate of a limestone pavement grike has been observed to provide a moderating impact on the regional temperature and may, in theory, serve to provide a habitat for such species whose range has contracted. Such protection is not without precedent, as was discussed previously the Rigid Buckler-fern was once more widespread before grazing pressures restricted much of their range to the protection of grikes (Jermy, Arnold, Farrell & Perring, 1978).
Under the same conditions, the range of species may also expand presenting a new range of challenges for management. Threatened species such as the spring gentian (*Gentiana verna*), Limestone fern (*Gymnocarpium robertianum*) and ladies' tresses (*Spiranthes spiralis*) are all limestone pavement species with a level of scarcity but are predicted to experience an increased range under a temperature change of + 2°C (Price et al., 2018). While this range expansion may be positive for the species involved, species such as these and others may expand their ranges into habitats for which they are not typical. One such example is the Wall Lettuce (*Mycelis muralis*), which was not found on The Burren until the 1930s and was found to be prevalent in limestone pavement grikes by the end of the century (Clabby & Osborne, 1999, Osborne, 2003). *M. muralis* is widespread in Europe; however, predictions of distribution in warmer future climates show a progression of both the leading and trailing edge of the distribution toward higher latitudes (Price et al., 2018). This non-native species is considered "invasive" in the Republic of Ireland and is hypothesised to compete with similar co-occurring species in woodland (Clabby & Osborne, 1999). The adaptive advantage of comparatively thermophilic species and their presence in habitats may result in other species being supplanted resulting in disruption to the food web of their new habitat (Petchey, McPhearson, Casey & Morin, 1999; Thomas et al., 2011). One such disruptive species is the heath false brome *(Brachypodium pinnatum)* which is reportedly resistant against molluscs and has been observed to outcompete other calcareous grass species (Hurst & John, 1999; Buckland, Hodgson & Grime, 2001). Further disruption may be caused by the flourishing or the introduction of species which may impact the health of species in a less direct way than the competition for resource. The breeding season for rabbits is hypothesised to extend due to the predicted effects of climate change. As a result, grazing pressure may increase on limestone pavements and the on neighbouring grassland (Tablado & Revilla, 2012). There are indications that diseases to plants and animals are spreading into new territories as the climate changes (Freer-Smith & Webber, 2017). These diseases may have direct impacts on individual species which inhabit the limestone pavement habitat or effects to neighbouring habitats may have knock-on effects by disrupting food sources (Freer-Smith & Webber, 2017). Further indirect impacts may influence the limestone pavement biodiversity through increased pesticide spraying on agricultural land (Izaurralde et al., 2011). This reaction by farmers to increased pathogen threat may exacerbate the existing issue of pesticides drifting onto limestone pavements (Spiteri, 1991).

It is the challenge of conservation under climate change to assess the impact of species migration and effectively manage the impacts (Heller & Zavaleta, 2009; Loss, Terwilliger & Peterson, 2011; Gillson, Dawson, Jack & McGeoch, 2013).

2.4.4.4 Microclimate, refugia and climate change

The applicability of general climate projections must be taken with caution, as it has been shown thus far that the microclimate within the limestone pavement grike is more thermally stable, more humid and more shaded than outside the grike. Climate projections created by the Intergovernmental Panel on Climate Change (IPCC) (Pachauri et al., 2014) rightly consider the planet as a system and identify broad-scale trends for countries and regions. In Britain, the United Kingdom Climate Projections 2018 (UKCP18) (Murphy et al., 2018) have used global climate projections based on a range of emissions scenarios, to quantify the effects of climate change on smaller regions of Great Britain. The spatial scales of climate predictions are often mismatched to the spatial scale at which species operate (Hannah et al., 2014). This mismatch in spatial scale does not account for areas in which the effects of climate change are reduced or even non-existent; these areas have been dubbed refugium.
A Refugium, or in the plural refugia, was originally used to indicate a large area in which organisms were protected from a historical climatic change such as during glacial advances and retreats after the Last Glacial Maximum (LGM). It is argued that these refugia acted as a foundation for colonisation during more favourable climatic periods (Hewitt, 2000; Davis & Shaw, 2001; Stewart & Lister, 2001). The terms refuge and refugium have been used interchangeably to describe “microhabitats providing spatial and/or temporal protection from disturbances or advantages in biotic interactions” (Keppel et al., 2012). In the literature on this subject, refugia fall into the two main categories of macro- and microrefugia, these fall on a sliding scale; however, microrefugia may be distinguished by requiring finer scale understanding of local climate than are found in commonly used climate grids (Ashcroft, 2010).
Examples of large scale refugia or macro refugia occur in Europe on the Iberian Peninsula, Southern Italy, the Balkans, and are widely accepted as climatic refugia for thermophilous (warm-loving) species during the LGM (Hewitt, 2000; Jackson & Overpeck, 2000; Jackson et al., 2000; Birks & Willis, 2008). Although refugium is the term used to describe a large area within which species survived periods of glaciation during the LGM (Bennett & Provan, 2008; Keppel et al., 2012), there is growing evidence to suggest that in addition to the landscape scale refugia described, there are also smaller local scale refugia which occurred over the same periods of time (Willis & Van Andel, 2004; Birks & Willis, 2008). The term ‘microrefugia’ is now used to describe areas of favourable microclimate for low-density populations or populations which require smaller sized habitats to remain viable (Birks &

Willis, 2008; Provan & Bennet, 2008; Ashcroft, 2010). The possibility of such microrefugia and their potential role during the LGM is under debate (Tzedakis et al., 2013; Hylander et al., 2015), as it is sometimes claimed that the presence of fine-grained heterogeneity in itself will buffer species against the effects of climatic change (Willis & Bhagwat, 2009).

The body of evidence discussed thus far indicates that refugia and even microrefugia have served a vital role in the survival of species during climatic changes in the past. There is also a growing body of evidence to suggest that climatic refugees may have a role to play in the survival of species in future climate changes to come (Prosser et al., 2010). Modelled alpine habitats are showing that although the regional climate may change over time, there are local-scale refugia in which species under threat may persist (Randin et al., 2009). On a smaller scale, models of habitat in Snowdonia have shown varying survival success for ground beetles based on microclimatic variation (Gillingham, Huntley, Kunin & Thomas, 2012). These small-scale climatic changes often occur as a result of variation in topography such as slopes and rocky features (Gunton, Polce & Kunin, 2015; Maclean et al., 2015).

Due to the scale of the microclimates in limestone pavement grikes any discussion of refugia in grikes will be in terms of their viability as a microrefugia. It is, however, notoriously difficult to identify habitats which will become microrefugia in the future. One author stated that “their precise characteristics, besides the also speculative but necessary occurrence of favourable microclimates, are unknown” (Rull, 2009). Some authors have hypothesised that thermal sheltering such as vegetative cover (Suggitt et al., 2012) and variation in microhabitats (Macgregor & van Dijk, 2014) can lead to microrefugia, but most agree that a combination of factors contributes to the formation of microrefugia (Hannah et al., 2014). The presence of a relatively stable microclimate and habitat variation has led limestone pavements to be described as a refugium for flora in open sites, which today may be called a microrefugium (Ward & Evans, 1976). There is also evidence to suggest that limestone pavement grikes still harbour some relict woodland plant species from the Late Devensian and early Holocene (Ingrouille, 2012), presenting the possibility that limestone pavement grikes may provide microrefugia for flora and fauna during the anthropogenic climate changes predicted in the future. However, like many habitats, the limestone pavement may be under threat from the influences on biodiversity from climate change (Walther et al., 2002; Parmesan, 2006).

2.4.4.5 Examination of the debate for the management of habitats for climate change

The role of land managers to influence habitats under climate change is contentious and falls under the banner of “post-normal science” (Hulme & Turnpenny, 2004). This term was proposed by Funtowicz and Ravetz (1993) to describe the conduct of research where facts are uncertain, traditional methodologies are ineffective, and the outcome is of huge importance. This term describes the management of habitats for climate change, because the climate models used have a degree of error and are contended, the predictions for species dispersal are contested, the management used must be adapted, and the stakes for success are very high (Guisan & Thuiller, 2005). This amount of uncertainty has led to several debates; these are explored in this literature review and focus on the respective roles of resistance, resilience and facilitation to manage habitats for climate change.

2.4.4.5.1 Resistance

Resistance to climate change includes actions which actively resist change within habitats. These resistance actions often include pre-existing management that intensifies in scope and concentration as climate changes progress. Actions such as the removal of “invasive” species will snowball, as climate change causes increasing numbers of atypical species ranges to overlap a protected habitat (Hellmann, Byers, Bierwagen & Dukes, 2008). Some resistance measures may include new actions such as the construction of windbreaks to shelter species or active management of hydrology to feed drying marshes (Burkett & Kusler, 2000; Cochrane & de Vries, 2014). Resistance to climate change is often a short term intensive action because the status quo is being maintained at great cost and if actions are too prescriptive may increase long-term habitat damage (Harris, Hobbs, Higgs & Aronson, 2006; Millar, Stephenson & Stephens, 2007). Adoptions of these strategies are considered until other measures can be taken to adapt a habitat or to relocate species (Millar, Stephenson & Stephens, 2007). Application of resistance actions are often value-driven and protect keystone species or those at greatest risk (Heller & Zavaleta, 2009). Short term resistance to an imminent threat may be worth the cost in some habitats such as refugia which may serve to protect species in the long-term (Rull, 2009). The actions discussed here are generally understood not to be a long term solution as there is a wide consensus that there is no static status quo and habitats must be adapted to the impacts of climate change (Hagerman, Dowlatabadi, Satterfield & McDaniels, 2010).

2.4.4.5.2 Resilience

Change resilience actions seek to promote gradual change within a habitat while aiming to encourage recovery from disturbance so as not to trigger a critical shift to a stable state dominated by "invasive" species (Galatowitsch, Frelich & Phillips-Mao, 2009). Effective resilience plans to diversify habitats often take place through adaptive management (Holling, 1978) where detailed monitoring and incremental action allow a flexible evidence-driven approach to management (Walters & Holling, 1990) which can be as easily reversed as enacted (Lindenmayer & Burgman, 2005). Some practices used in resistance are also used in resilience in order to course-correct and avoid the critical shift. However, they are often applied more broadly and include other landscape-level actions (Millar, Stephenson & Stephens, 2007). These landscape-level actions may include increases in landscape heterogeneity to allow species to escape disturbance such as drought (Galatowitsch, Frelich & Phillips-Mao, 2009). In extreme cases, land managers may bank excess seeds to repopulate a habitat after a large disturbance (Millar, Stephenson & Stephens, 2007). Resilience actions are often taken after a form of triage where climate threats, resource limitations, ethical concerns and multiple other factors are considered, and decisions concerning a habitat are taken for "the greater good" (Macgregor & van Dijk, 2014; Wilson & Law, 2016).

Change resilience is the most commonly suggested adaptive option used by land managers and as a general concept gains wide support (Millar, Stephenson & Stephens, 2007; Brown, 2015). The degree to which resilience should promote gradual change is an area of disagreement among the scientific community. Some take the point of view that habitats should be allowed to change their dynamics and species, inevitably leading to some extinction and to completely new ecosystem classifications, whereas others are more reticent about allowing such drastic change and highlight the difficulty of predicting what is best for each habitat in the future (Hagerman, Dowlatabadi, Satterfield & McDaniels, 2010). One study highlights the general agreement that previously "Taboo" actions such as "forgoing attention to target species deemed no longer viable", were now open for consideration; however, conservation experts retain discomfort in accepting such actions (Hagerman & Satterfield, 2014). This discomfort has led to worries that public perception of conservation could suffer and there would not be a public appeal for new ecosystems which no longer resemble those which were once popular (Hagerman, Dowlatabadi, Satterfield & McDaniels, 2010). Discussion of the motivation behind specific resilience measures in East Anglia indicates that the incremental embrace of transformative change is dictated by the realities faced and discomfort around taking such action is moot. The scientific community are certainly not of one mind about resilience actions; however, published sources suggest that the acceptance of change is growing despite the unease with which it is accepted.

2.4.4.5.3 Facilitation

Facilitating climate change through our actions includes measures which intentionally accommodate change rather than resist or allow it to occur passively (Millar, Stephenson & Stephens, 2007). Actions included in facilitation focus on pre-empting the range shift by species and opening up corridors to ease the migration or actively translocating species to a new habitat where they may be expected to thrive (Galatowitsch, Frelich & Phillips-Mao, 2009). Facilitation is the least popular of the management options to be proposed. However, there appears to be a divergence of opinion when considering the method by which change is facilitated. Connecting landscapes using corridors appear to meet little resistance with one conservation scientist stating that they are "one of the best things we can do to protect big landscapes".

Conversely actively transplanting species through assisted migration meets strong resistance as sceptics claim that we do not know enough to start playing god and that such meddling is doomed to failure (Hagerman, Dowlatabadi, Satterfield & McDaniels, 2010). There are however advocates of this action who claim that we have a small opportunity window in which to act and do not have the luxury of time to satisfactorily prepare (McLachlan, Hellmann & Schwartz, 2007). Despite the reluctance to undertake assisted migration, some specialists agree that circumstance will force land managers to resort to this option. However, the accepted level of risk that will force this action is still under debate (Hagerman, Dowlatabadi, Satterfield & McDaniels, 2010; Brown, 2015).

2.5 Summary

Karst features such as limestone pavements develop over extremely long periods, involving multiple processes. In Britain and Ireland, this confluence of specific events has resulted in several discrete areas of limestone pavements. The unique nature and long-time scales involved in limestone pavement creation make them irreplaceable landscape features. The habitat found within grikes is home to a distinctive community of species underpinned by the structure of the limestone pavement and the stabilising microclimate it creates within the varied forms of grike (Willis, 2011). This link reinforces the notion that the geodiversity of the structures within a single limestone pavement may underpin the variation in biodiversity. The limestone pavements of Great Britain and the Republic of Ireland are recognised for their contribution to the biodiversity and geodiversity of Britain and Ireland through several protections afforded to them. Though these protections are numerous, damage still occurs on limestone pavements through intentional and unintentional actions and neglect. Like many other habitats, limestone pavements face challenges of climate change; however, due to their distinctive microclimate, some may become microrefugia for species escaping climate change. Land managers urgently require the research on which to base difficult decisions for species and habitats. This thesis seeks to add to the research from the fields of Climatology, Fluid dynamics and Ecology, which relate to the issues discussed in this chapter. It is intended that the conclusions of this research will guide the direction of future research needed to inform how to protect and utilise aspects of this exceptional habitat for the greatest effect over the coming turbulent years.

3. Methodology

3.1 Philosophical grounding

3.1.1 Research philosophy

The subject of conservation assessment techniques is explored at great length concerning the limestone pavements of Yorkshire by Usher (1980). In this work Usher (1980) describes that many of the measures used to assess the conservation value of a site are subjective and that the Malham-Arncliffe SSSI is most effectively evaluated by assessing SSSI size, diversity of species and habitat, and rarity of species. The research philosophy employed is not explicit by Usher (1980); however, the focus on the more factual elements of the site is strongly argued.

This thesis and the methodologies used are grounded in the Positivist paradigm. The Positivist paradigm is most fitting to the research being undertaken because the nature of the phenomena being investigated can be tested empirically without socially constructed realities (Trochim & Donnelly, 2006). The Positivist ontology states that the nature of reality is understood to be independent of the observer and not to be time or context-bound. All effects are governed by laws which consist of pre-existing stable patterns which may be predicted and generalised (Trochim & Donnelly, 2006). Following on from this ontology the Positivist epistemology for this research states that knowledge of the subject matter can be verified based on laws and that these laws hold true for multiple situations (Trochim & Donnelly, 2006). To this end, the methodology proposed has endeavoured to identify the observable laws governing the grike microclimate and use these laws to hypothesise how changes to the external climate will impact the grike microclimate and by extension the inhabitants of the grike.

3.1.2 Conservation philosophy

The term "conservation" is used in several fields, can mean different things and can encompass a great number of approaches. The ambiguity of this term is why it is important to understand what is meant by conservation in the context of this thesis and for the methodology used.

Conservation in the context of nature is defined in several ways; however, there are several core ideals which hold throughout numerous definitions. These core features include sustainability and the maintenance of essential ecological processes, biosphere function and genetic diversity (Canney & Hamdler, 2013; Dyke, 2008). Alongside these ideals, more recent definitions introduce the conservation of geodiversity and archaeological features for the information they can provide about past environments (Gray, 2013; Canney & Hamdler, 2013).

Within these definitions of conservation, different conservation philosophies may interpret the act of conservation from different motivations and seek differing outcomes. Utilitarian and nonutilitarian are two main schools of thought when considering the philosophy of conservation. Utilitarian philosophy holds that nature has consumptive, aesthetic and service value to people and should be conserved because of this, whereas non-utilitarian philosophy holds that nature should be conserved for reasons other than those of utility. The non-utilitarian philosophy can be further subdivided into the intrinsic value of species which holds that species have a right to exist, and extrinsic value which believes that the knowledge of species existence has value to people (Canney & Hamdler, 2013).

This thesis has been written from the non-utilitarian perspective of nature's intrinsic value, that is to say, that that it is morally right to conserve nature aside from human interests and to repair the damages inflicted on the natural world as a by-product of human progress. To this end, this thesis holds that "diversity of organisms is good" and that "ecological complexity is good" as stated in the normative postulates of conservation biology (Soulé, 1985). This thesis does, however, acknowledge that "conservation must occur within human-altered landscapes" as stated in the Normative postulates of Conservation Science (Kareiva & Marvier, 2012).

3.2 Methodological approach

3.2.1 Review of methodological structures

The second aim of this thesis focuses on identifying the research which is needed in order to improve the evidence base on which effective climate adaptation guidance is based. In order to fulfil this aim and provide the resources required for the first aim, the methodological structure of this thesis was organised using established climate adaptation literature.

In 2015 Natural England proposed a resource for land managers, management advisors, and environmental consultants to support practical and pragmatic decision-making in management for climate change. This "Climate Change Adaptation Manual" focuses on four tenets:

1. Understand the changes in the climate that are likely to occur in your region.

Using regional climate projections and local knowledge about how the surrounding area has been affected by weather-related events in the past, proposing a series of realistic possible future possibilities is possible.

2. Recognise the intrinsic sensitivity of the species, ecosystems and other features on the site to those climatic changes

By applying local species knowledge and researching the inherent climate tolerance that species have for certain conditions. It may be possible to estimate the level of risk species face from the changes hypothesised in section 1.

3. Identify the Site-specific conditions that could make things better or worse

Characteristics of a site can either reduce or exacerbate the effects of climate change. Some habitats are more susceptible than others to particular changes, such as flooding or drought, or areas of the site may experience greater temperature fluctuations. Additionally, if ecosystems and habitats are already in poor condition, they may be less likely to cope with additional stresses.

4. Acknowledge the capacity to manage those conditions

Sections one, two and three provide an expectation of the management required. However, the range of management options available to each site can be limited both within the site and beyond its borders. Options may be limited by the site's management history, intrinsic sensitivity of features, access and numerous other factors.

(Natural England, 2015)

This four-item method is a UK government recommended outline for approaching the issue of management under climate change. This document is intended to provide a resource to bridge the gap between the academic and the practical. Natural England's guidance has a strong emphasis on collecting a strong evidence base before action both in terms of climatic effects and the sensitivity of the habitat. This manual also acknowledges the limitations to practical climate change adaptation both in terms of available management options and the effectiveness of any intervention (Natural England, 2015). This consideration is especially important in the UK where at the local level, short term statutory duties take priority over long term climate change (Porter, Demeritt & Dessai, 2015). Although Natural England's guide (2015) is not a stepwise method, it could be adapted by switching steps two and three.

Both the EPA in the Republic of Ireland and the NWF (National Wildlife Federation) in the United States of America propose a stepwise approach to habitat management for climate change.

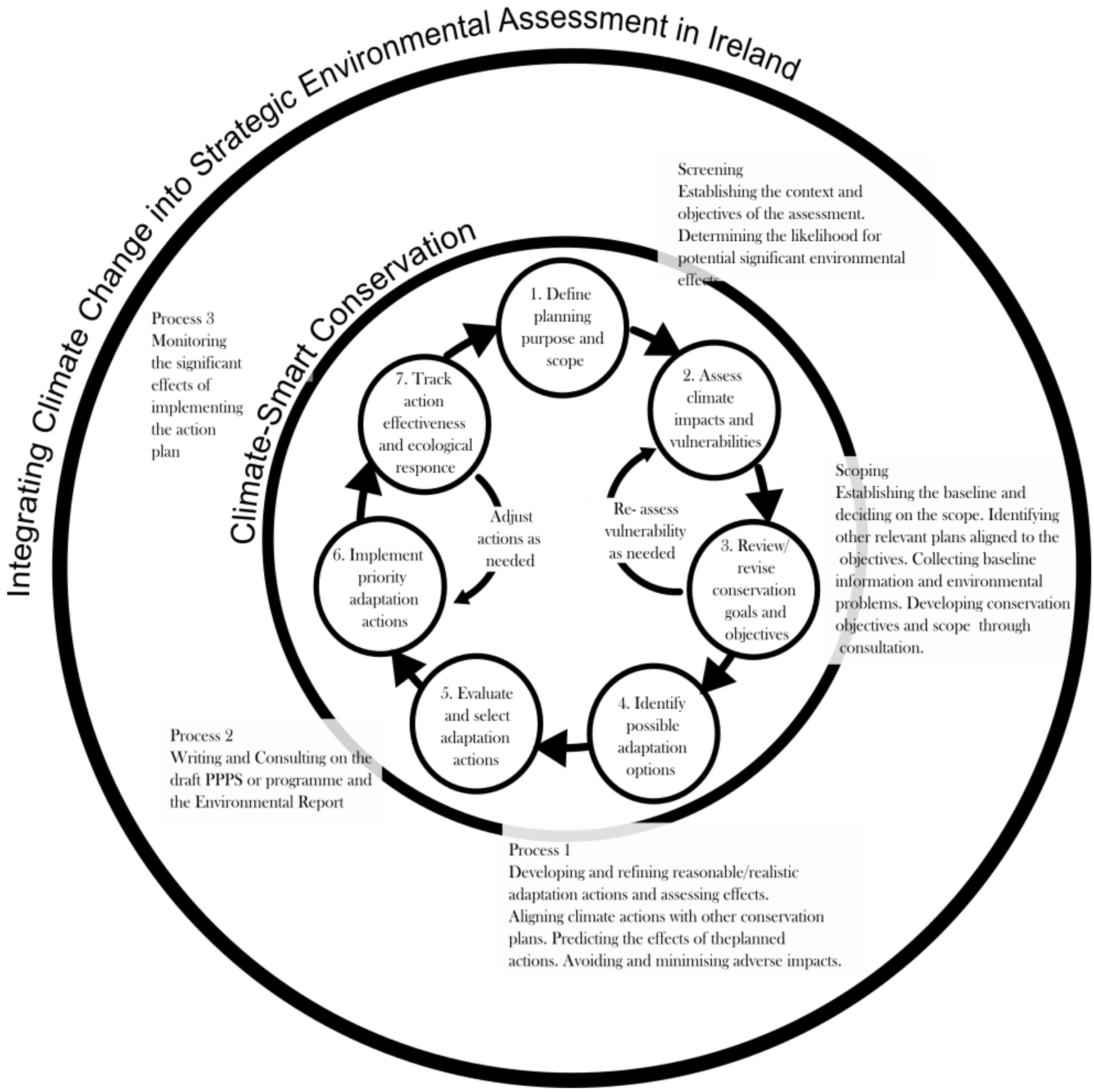


Figure 3.1 Stepwise conservation from the EPA's guidance "Integrating Climate Change into Strategic Environmental Assessment in Ireland" and the NWF's guidance "Climate-Smart Conservation" (Environmental Protection Agency, 2015; Stein, Glick, Edelson & Staudt, 2014).

The EPA's guidance "Integrating Climate Change into Strategic Environmental Assessment in Ireland" is a document to integrate climate change into the existing Strategic Environmental Assessment (SEA) framework (Environmental Protection Agency, 2015). This document takes a wider view than the Natural England guidance and incorporates consultation, process monitoring and other tasks which are peripheral to the direct task of management. Likewise the NWF's document "ClimateSmart Conservation" takes a broader view of climate change adaptation by providing steps to take after each intervention in order to monitor the effectiveness and create a feedback loop (Stein, Glick, Edelson & Staudt, 2014). This document has been widely adopted in the conservation literature and adapted to suit multiple purposes, including the conservation of refugia (Morelli et al., 2016).

3.2.2 Methodological structure

The methodology proposed in this study has drawn heavily from the approach taken by Natural England and attempts to provide preliminary research for all four tenets of climate change management planning. This methodology has also drawn certain peripheral elements of climate change adaptation from the Irish and American documents to strengthen the evidence base for future researchers.

All the recommended approaches to climate change adaptation suggest conducting prior research into local level climatic impacts, site-level barriers to management and scoping the crosscutting conservation strategies in place (Stein, Glick, Edelson & Staudt, 2014; Environmental Protection Agency, 2015; Natural England, 2015). This work has been begun as part of a literature review that establishes this thesis within the context of current research, and from this methodology that assesses the site suitability and provides a basis for research. The further chapters of this study have been reported in three major phases which have been adapted from the recommendations discussed:

1. Conduct a preliminary examination of the characteristics that could make impacts of climate change better or worse through direct measurement and computer simulation of microclimate in grikes.
2. Develop and refine these assumptions using a preliminary modelling exercise to simulate the future grike temperature.
3. Consider the intrinsic importance of the grike to species of invertebrate by gaining a greater degree of species-level understanding and explore the relationship between invertebrates and the grike microclimate.

In order to undertake these phases, multiple disciplines were explored as sources of information.

Phase One

- Discipline: Systems theory, Subdiscipline: Climatology

  A microclimate based investigation is used in order to understand how the form of a limestone pavement grike affects temperature, light intensity and relative humidity.
- Discipline: Engineering, Subdiscipline: Fluid dynamics

  Computational fluid dynamics is used in order to investigate how the form of grikes influences airflow. Phase Two
- Discipline: Systems theory, Subdiscipline: Climatology

  Climate simulation uses data and conclusions from Phase One in order to recognise how grike form may influence future microclimate Phase Three
- Discipline: Ecology, Subdiscipline: Ecosystem ecology

  Conclusions from Phases One and Two are used in order to understand the relationship between the microclimate and the invertebrates of the grike.

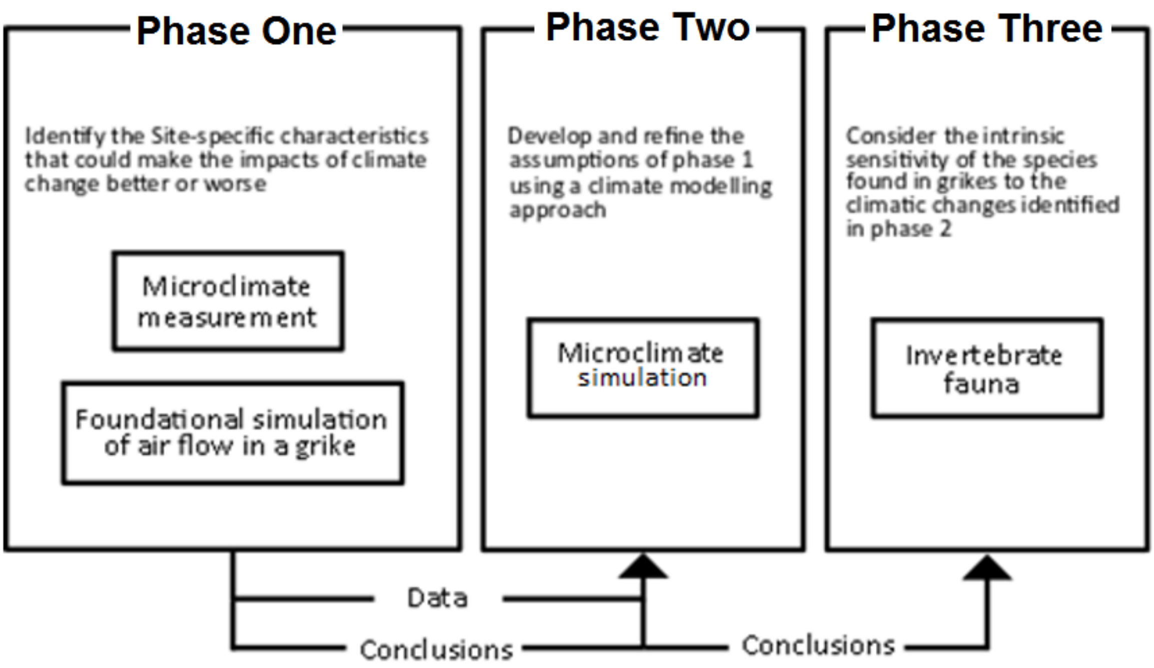


Figure 3.2 Conceptual model of the structure of the thesis.

3.3 Site selection

In order to undertake the fieldwork conducted in Phases One and Three of this work, sites for research were selected. The sites chosen in the following subsection are used for the fieldwork reported in Chapters Four and Eight of this thesis.

3.3.1 Site selection rationale

There is an emphasis on the inherent character of a site in the climate change adaptation literature and how it can influence a habitat's reaction to climate change (Suggitt, 2012; Hannah, 2014). With limited resources, it was not possible to include the entire range of pavements in this study. It is, for this reason, a method of optimising the diversity of pavements studies was required.

Although unpublished, the thesis "Classification and management of limestone pavements – an endangered habitat" (Willis, 2011) provides a way of economically sampling from as broad a range of pavements as possible. In Willis' thesis, a holistic system of limestone pavement classification was created. This used 75 variables over 46 UK limestone pavements to provide six distinct groups of pavement as defined in Table 3.1; hereafter these will be known as "Groups".

Table 3.1 Descriptions of the pavement Groups (Willis, 2011).

Group	**Limestone pavement description**
Group 1	High altitude, open limestone pavement with medium-range grike depth (0.5-1m) and small clint size. Low species richness, though typically rich in fern species. Indicators include *Urtica dioica*, *Asplenium viride* and *Cystopteris fragilis*. Group 1 incorporates the two pavements from Group 2, as these Groups share many features in common.
Group 3	Open limestone pavement, proximal to the coast (<15km) with little moss growth and largely unvegetated clints. The typical dip is between 5-25°. High in "negative" species, lower levels of precipitation and ground frost. Indicators include *Ulex europaeus* and *Sonchus spp*.
Group 4	Wooded, mossy, species-rich limestone pavement. Typically dip is 10-40°, grikes 0.75m deep and 0.2m wide, and runnels are frequent. Indicators include *Rhamnus cathartica*, *Dicranum scoparium* and *Thamnobryum spp*.
Group 6	Species-rich, open limestone pavement. The high presence of limestone pavement specialist species. Thickly-bedded (>0.6m) with grikes typically over 1m deep. Indicators include *Anthoxanthum odoratum*.
Group 7	Level limestone pavement, typically above 450m, with shallow, wide grikes, generally <0.5m deep and >0.25m wide. Low species richness, particularly trees/shrubs/ferns and pavement specialist species. Low sward (<40mm) with medium to high grazing. Indicators include *Oxalis acetosella* and *Luzula campestris*.
Group 8	Wooded, low altitude limestone pavement, proximal to the coast (<15km). Typically with narrow grikes around 1.1m deep, dip 10-20° and long, narrow runnels. Indicators include *Betula pendula*, *Quercus spp*. and *Taxus baccata.*

Throughout her thesis, Willis makes the case that limestone pavements are categorised into distinct Groups based upon the proposed holistic criteria. Aside from some exceptions discussed later, all limestone pavements in the UK can be categorised based on these criteria and guidance for management can be proposed based on these groupings. Given the availability of the classifications from Willis and the guidance on climate change management, it was logical to suggest that in order to provide research applicable to a wide range of limestone pavement grikes, this study would endeavour to include a wide range of pavement classification Groups.

As mentioned previously, there are limitations to Willis' classification for this study. By the author's admissions, there were three pavements which could not be classified. Two pavements were not included in the analysis due to their small size, and the third was "substantially different to the other limestone pavements" making up its own Group included in analysis. These limitations indicate that the classification groupings are not exhaustive and cannot be used on "very small" pavements though how small is not specified. Willis' thesis also indicates that further work could sub-classify "bucket" Groups 1 and 3. These Groups contain sites which are distinct from other Groups, however also contain a wide diversity of pavements, leading the Willis to recommend that further subclasses may be possible.

Willis's classifications were created solely on UK limestone pavements, differentiating Groups by the depth and width of the grikes, the altitude of the pavements, the proximity to the coast and the amount of wooded cover. These metrics may apply to the UK but may limit their applicability to use on the sites selected for study on The Burren in the Republic of Ireland.

Depth and width of the grike depend upon the thickness of the bedding plane (Willis, 2011), the composition of the limestone and the amount of weathering received (Viles & Trudgill, 1998). Willis' grouping system was developed on the Carboniferous limestone of the UK, which varies regionally. The limestone is characterised by shallow (0.5) to thick (2.5m) bedding planes and containing a variable composition and purity of limestone, due to the period of the Carboniferous in which each stratum was deposited (Willis, 2011). The limestone of The Burren was also deposited in the Carboniferous period and described as medium to thickly bedded. There is also a great amount of variation in the character of the limestone from the relatively pure Finavarra Member, the dolomitised limestone in the Fanore Member to the cherty limestones in the Balliny Member (McNamara, & Hennessy, 2010).

After the limestone's formation, mechanical weathering and chemical weathering by CO_2 may create grikes, which are different from those viewed by Willis (Sweeting, 1966; Zseni, Goldie & Bárány-Kevei, 2003). When compared to the Northwest of England and the North of Wales, where Willis conducted her work The Burren experiences a smaller range of temperatures over the year and marginally lower average. The smaller temperature range reduces the possible impact of freeze-thaw weathering, and lower wind-speed may reduce abrasion on the rock (Carroll, 2012). Research by Ballabio et al., (2017) describes the erosivity of rain in The Burren to be higher than that of most of the area where Willis conducted her work, indicating that chemical weathering may be higher in The Burren. Based on this information, it is difficult to estimate the resultant impact weathering may have had on the shape of grikes.

Higgins (2014) explored the applicability of Willis' groupings to pavements on The Burren and concluded that many of those she explored contained deeper grikes than were found in most of Willis' work. Based on the available information, it can be stated that both areas contain a wide variety of depths and widths of grike, but The Burren contains several sites with extremely deep grikes not found in the UK.

Pavements above an altitude of 275m were considered by Willis to be "High Altitude" though many are typically above 450m. The highest point in The Burren is Slieve Elva (344 m) (McNamara, & Hennessy, 2010). This point is lower than the typical range for a "High" Altitude" pavement (Willis, 2011). Pavements considered "Proximal to the coast" by Willis are those up to 15km away from the coastline (Willis, 2011). In The Burren, there is only a small area near the village of Corofin in the Southeast, which is greater than 15km from the coast. The differences in altitude and coastal proximity on The Burren, when compared to the UK, mean that Willis' tolerances would have needed to be revised to apply to The Burren.

Grassland habitat dominates both The Burren and regions of the UK with Limestone pavements. Wooded cover for the limestone pavements in the UK is uncommon, however wooded cover is rarer still in The Burren (Williams, 1966; Ward & Evans, 1976). The limestone pavements of The Burren are managed for their open character, and scrub management is one of the core activities of managing The Burren (Burrenbeo Trust, 2016). This emphasis on open pavements largely rules out groupings from Willis which focus on the pavement's wooded cover.

Based on the differences between the character of the limestone pavements in the UK and The Burren, Willis' classification system has not been applied on The Burren. Based on this exploration, it has been identified that The Burren region is more coastal and lower in altitude than most sites explored in the UK, and extremely open due to the lack of wooded pavements. From personal observations and those of Higgins (2014), there are also considerably deeper grikes found on The Burren than have been found in the UK.

3.3.2 Site selection methodology

Sites in the UK were chosen primarily based upon Willis's limestone pavement classifications (Willis, 2011). Previous studies (Heslop-Harrison, 1960; Silvertown, 1982) have found, however, that as the depth of a grike increases, the microclimate becomes more stable. It is for this reason that the highest priority was given to Groups 3 and 6 when selecting sites as these represent the majority of the deepest grikes which provided the greatest scope for testing the stability of the microclimate (Willis, 2011). Group 3 contains open, coastal limestone pavements with little moss growth and un-vegetated clints and Group 6 contains higher altitude open pavements which are level, species-rich and thickly bedded. On The Burren, one site was selected from the coast, and one site found further inland and with deeper grikes, to represent the characteristics found more rarely in Great Britain.

Further priorities for selecting sites applied to all sites in this study. Priority was given to sites which provided a secure situation for equipment to be left without tampering. Previous investigations similar to this (Burek & Legg, 1999) were cut short due to the intentional theft or accidental clearing of equipment from a limestone pavement. To reduce the likelihood of damage to the equipment the access to a site such as a public right of way, visibility from roads and the popularity of a site were considered and where possible, local people were engaged as custodians to provide further protection between the collection visits.

Sites were chosen based on the direction of their joints. A study conducted by Burek and Legg (1999) concluded that the orientation of a grike directly impacts the amount of solar radiation or insolation that it receives. Based on this evidence, grikes were chosen at right angles to one another, preferably sited on the cardinal compass directions. The difference in grike orientation allowed for standardised orientation comparison in the analysis of results.

The location of a site and the ease of access for frequent data collection trips were considered based on the logistics of collection. The maximum capacity of the smallest memory data logger allows for an interval of 72 days between data collections. The capacity of the loggers required a minimum of 16 data collection trips for the longest-running site. Along with initial suitability visits, the site visits required a large amount of time and resources that increased with distance from the Chester base of operations. It is for this reason that sites for consideration were limited to North Wales, Lancashire, Cumbria, Yorkshire and the more accessible areas of The Burren. It was found by the author that limestone pavements as a whole, are rarely difficult to access from local roads; however, when a site needed special precautions the duration of study could have been limited or the site excluded.

The presence of large flora impacted on the choice of any limestone pavement site. Past study has found that trees and shrubs close to the limestone pavement can cause a build-up of leaves in the grikes (Burek & Legg, 1999). Large flora can affect the stabilising function of the grike and impact the results accordingly.

3.3.3 Site selection

3.3.3.1 Selection of sites

All the sites included within Susan Willis's study (Table 3.2) were mapped and visited to gauge their suitability. On each visit, it was considered how close the site was to human and road traffic, whether the prevailing joint direction lay on the cardinal compass directions and the ease of access to the site.

Table 3.2 Limestone pavements visited in Great Britain.

Group 1		Group 3		Group 4	
Name	Grid reference	Name	Grid reference	Name	Grid reference
Fell End Clouds	SD737998	Hutton Roof Crags	SD557776	Dalton Crags	SD552770
Great Asby Scar	NY657104	Holme Park Quarry Fell East	SD547790	Oxenber Wood	SD781683
Royalty Allotment	NY645105	Holme Park Quarry West	SD540796	Bastow Wood	SD994654
Sayle Bottom	NY655110	Holme Park Quarry	SD538788	Hampsfield Wood	SD402805
Sunbiggin	NY646090	High Farm Allotment	SD404791	Trowbarrow Quarry	SD481761
Clapdale Scars	SD749709	Bryn Alyn	SI198589		
Crummack Dale	SD772719	Great Orme	SH757839		
Sulber	5D774738	Y Taranau	SI182720		
Ewe's Top	SD704758				
Little Sainforth	SD810662				
Smearsett Copys	SD799683				
Hill Castles Scar	SD991684				
Hawkswick Clowder	SD947687				
Group 6		**Group 7**		**Group 8**	
Name	Grid reference	Name	Grid reference	Name	Grid reference
Scar Close	SD748771	Bordley	5D954648	Farrar's Allotment	SD451860
Top Cow	SD782759	Langcliffe	SD983721	Gait Barrows Wood	SD479772
Dale Head	S D840714	Lea Green	SD997662	Underlaid Wood	SD485790
Old Ing	SD782774	Cam High Road	S D854840	Bryn Pydew	SH817798
Malham Cove	SD897641	Greensett	SD747821		
Tennant Gill	SD8S1694	Rocky Ground	SD863735		
		Wold Fell	SD791850		

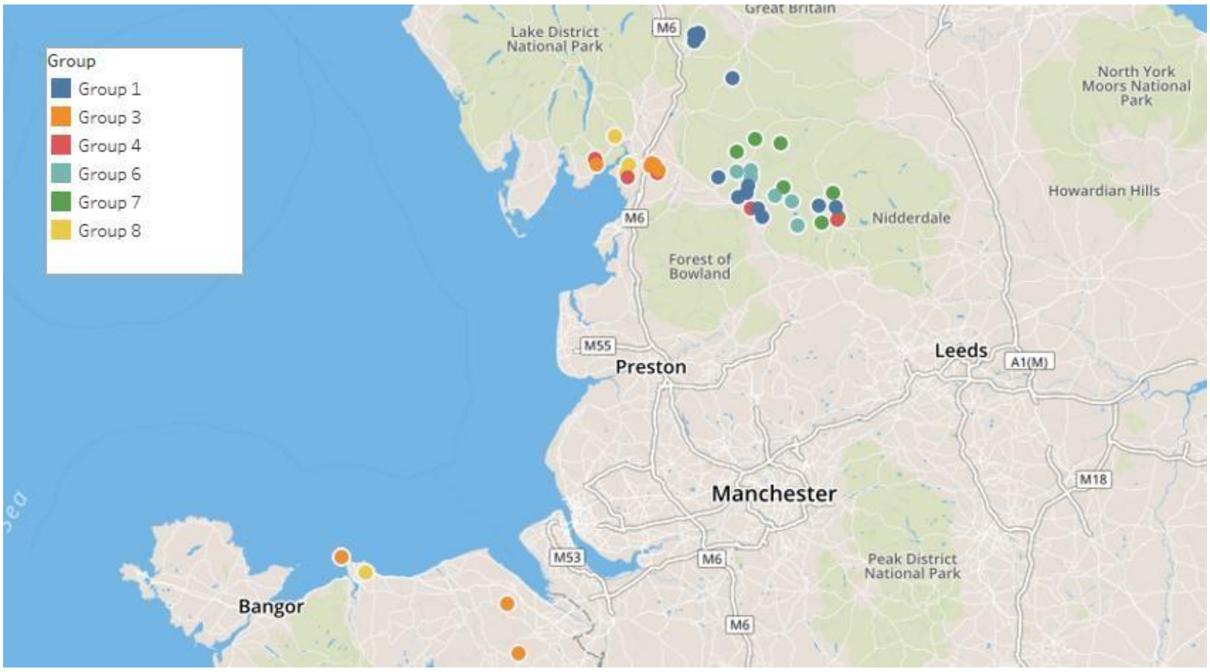


Figure 3.3 Mapped locations of sites visited in Great Britain.

From the initial list of pavements studied by Willis (Table 3.2), the sites in Figure 3.3 were visited. From those visited, the sites in Holme Park Quarry in Cumbria and Dale Head in Yorkshire were selected for their suitability for this study. These two sites are contained within Groups 3 and 6, respectively, which were designated as a high priority for this study due to their depth and potential for exemplary microclimates. All other pavements used in this study did not feature in Willis's study. However, efforts have been made to find sites which are within the same area as classified pavements or have featured in subsequent studies of limestone pavement Groups.

The Group 1 limestone pavements featured in Willis's study did not contain a site fully suited to the requirements of this research. It was for this reason that High Folds in Yorkshire (SD892681) was selected. High Folds is in the same pavement region as Group 1 pavements Little Sainforth, Smearsett Copys, Hill Castles Scar and Hawkswick Clowder. High Folds also shares the Group 1 characteristic of higher altitude, open situation, mid-range grike depth and low species richness. High Folds was also the site of Silvertown's (1982) influential study of grike flora and microclimate. The pavements situated in the Republic of Ireland were classified by Higgins (2014) who categorised Fanore on The Burren coast as Group 3 and Turlough More near Kilkeedy on The Burren, as either Group 1 or 3. In this study, however, the sites visited (Table 3.3; Figure 3.4) are used to explore the microclimate of extremely coastal situations found in Fanore and extremely deep grikes found in Turlough More.

Groups 4, 7 and 8 have not been included in this study due to the limited resources available. Group 4 and 8 are characterised as deeply wooded, densely vegetated and mossy pavement presenting a greater challenge than other sites, as grikes would regularly fill with leaf litter clogging the grike and influencing the microclimate (Burek & Legg, 1999). Group 7 contains sites with shallow and wide grikes, which are less suited to influencing microclimate. Group 7 is also typically heavily grazed, which may have caused disturbance to the data collection equipment and presents a threat to livestock.

Table 3.3 Limestone pavements visited in the Republic of Ireland.

Coastal sites		Deep sites	
Name	Grid reference	Name	Grid reference
Black Head lighthouse	M 15682 11640	Cathair Dhuin Irghuis	R 32694 95175
Goats Burren	M 16595 11085	Bare hills	M 21107 05469
Cathair Dhuin Irghuis	M 15788 11414	Berneens	M 22607 03859
Suggestion from John Burke	M 15458 11096	Corkscrew Hill	M 21230 02890
Murroogh East	M 14505 10005	Poulnabrone dolmen	M 23611 00431
Murrooghtoohy North	M 15152 10219	Moneen Mountainside	M 26671 08545
Shatterck	M 17426 09839	Eagle Rock	M 35181 04701
Fanore	M 11525 03927	Mullagh More	M 32792 00577
Poll Salach	M 09265 03394	Turloughmore	R 33300 98605
Poulsallagh	M 08631 01857	Eastern Fringe Pavement	M 38429 03610
Caher Valley Derrynavahgh	M 17404 04907		
Cappanawalla	M 19958 09018		
plateau of Cappanawalla	M 20712 08878		
Bare hills	M 21107 05469		
Doolin Quay	R 06073 97547		

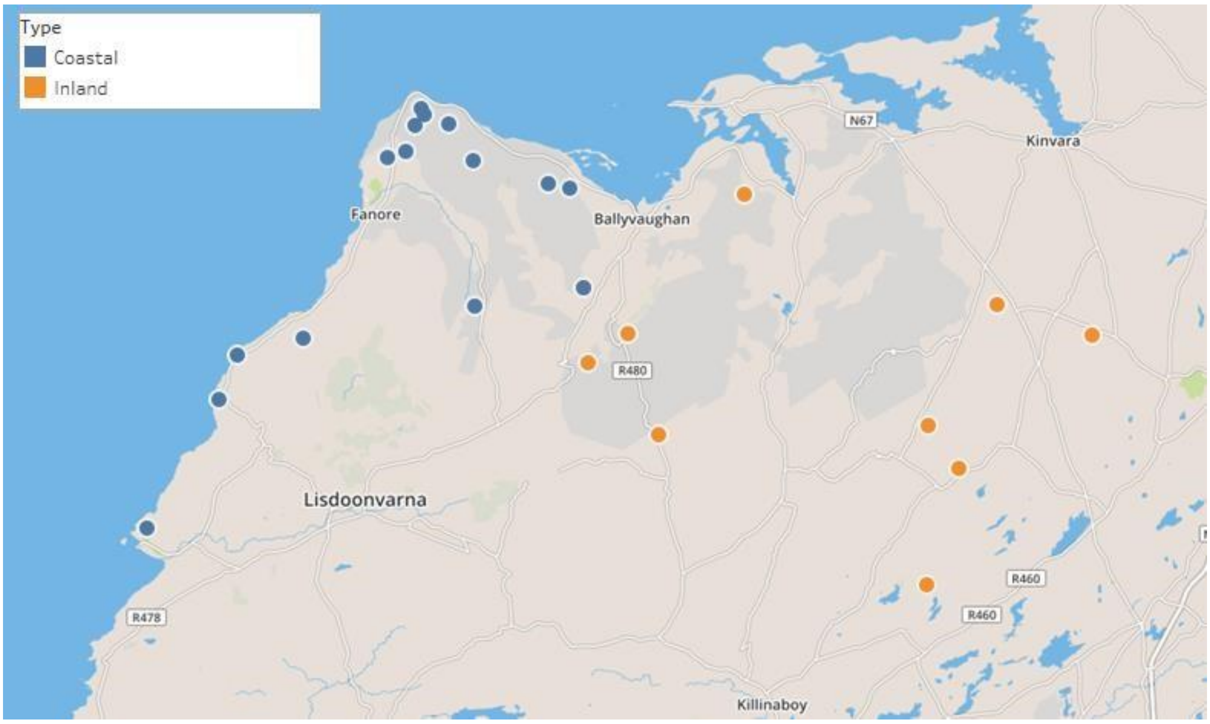


Figure 3.4 Mapped locations of sites visited in the Republic of Ireland.

<u>3.3.3.2 Representation of limestone pavements in Britain and Ireland</u>

As detailed above, the limestone pavements selected have been chosen to represent the Groups of limestone pavements to provide the most insights into the microclimate of grikes (Willis, 2011). In Subsection 3.3.2, further limits were placed on the limestone pavements available for long term microclimatic study. By using a diverse set of limestone pavement Groups, and a select Group of more specialised limestone pavements from the Republic of Ireland, this study has endeavoured to encapsulate as representative a range of limestone pavements as possible given the realities of conducting this research. This has meant that of the hundreds of pavements in Britain and Ireland and the 46 UK limestone pavements studied by Willis only three sites from Great Britain and two sites from the Republic of Ireland were selected for long term microclimate study. As a result, in some respects, this study did not represent all limestone pavements in Britain and Ireland.

Complete geographical representation has not been possible through this study. This has meant that pavements such as Rassal or Strath in Scotland could not be included. These pavements were formed on Cambrian or Ordovician limestone of the Durness Group as opposed to the Carboniferous limestone making up the pavements used in this study (Vincent, 1995; Waltham, Simms, Farrant & Goldie, 1997). These pavements also exist within a cooler and wetter macroclimate than are found in the rest of the study with an annual mean sunshine duration similar to The Burren (Met Office, 2016b). As a result of these features these pavements have an unusual variant of grike flora, and as a result of this flora and the macroclimate may also have a different microclimate (Joint Nature Conservation

Committee, 2019). It has also been identified later in this study in Subsection 6.3.2.2 that areas of North Wales such as the Isle of Anglesey have a warmer macroclimate than has been observed in the rest of this study, and as a result, may also have a slightly different microclimate. Likewise, the Muckross limestone pavement in the Southwest of Ireland experiences particularly high rainfall compared to other sites used in this study (Walsh, 2012).

As discussed previously in Subsection 3.3.1, Willis' Groups have been developed on pavements situated in England and Wales only (Willis, 2011). This presents the possibility that groupings may have been altered if sites from the rest of Britain and Ireland had been included and new groupings may have been introduced. If Willis' study had been conducted on the whole of Britain and Ireland, pavement Groups would encompass the features of a wider selection of pavements. A wider study would also provide a broader selection of limestone pavements from which to choose. This may have introduced greater and more varied microclimates for use by this study.

3.3.4 Summary of selected site locations

The selected sites were located in the Northwest of England and on the West coast of the Republic of Ireland on The Burren. Figure 3.5 shows the locations of the sites which were studied. The macroclimate, geology, anthropogeography and biogeography vary between these two regions. Anthropogeography is the distribution of humans within geographic space and the impacts which humans have on the environment in which they are found (Warf, 2010). Biogeography implies the linkage of Biology and Geography and studies the patterns in these two fields. An example of a study in biogeography may study the distribution of species, genetic variation, ecosystems or behaviour within the geographic space, which may include a range of habitats and latitude (Pears, 2014).

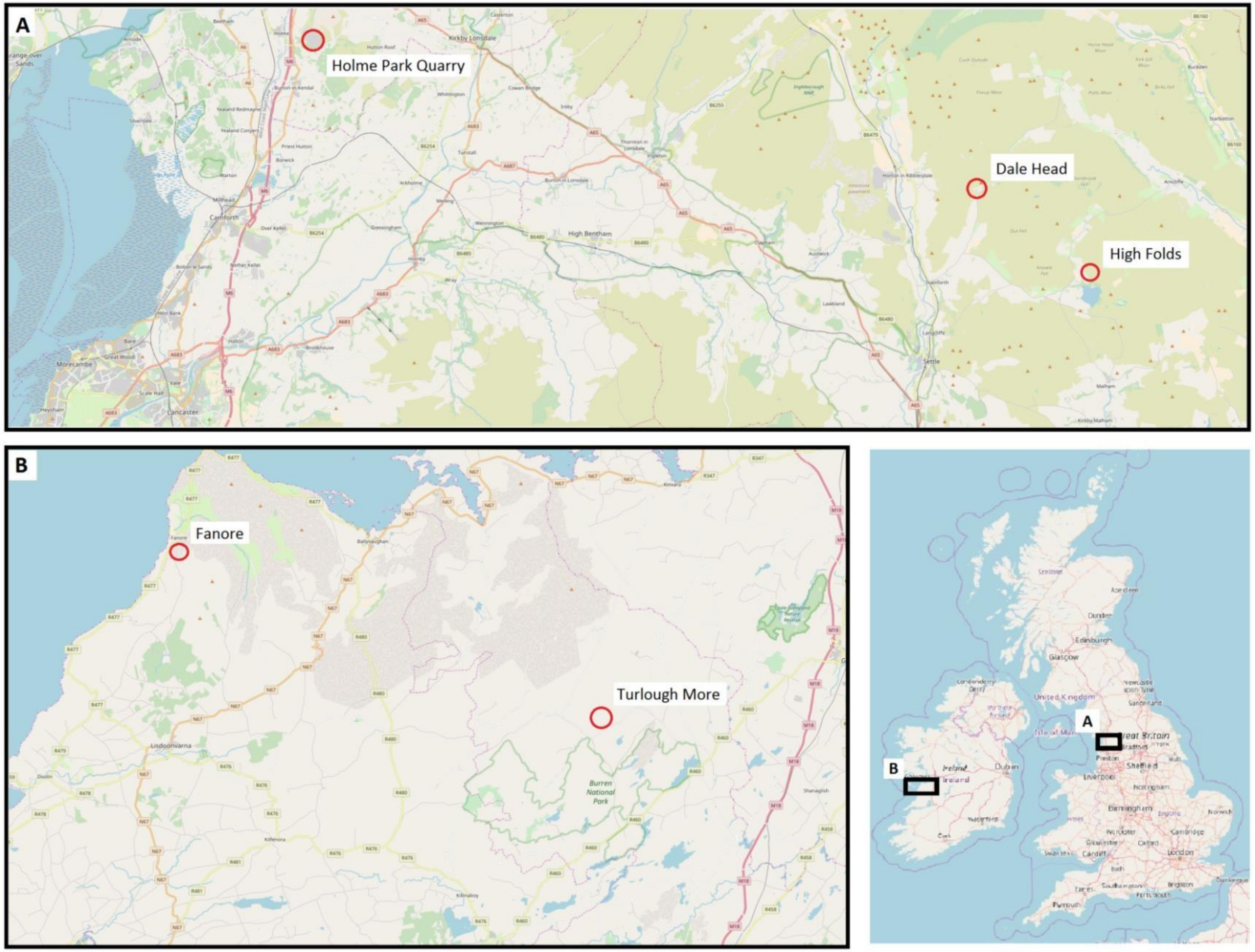


Figure 3.5 Locations of each of the limestone pavements under study (Open Street Map, 2017).Map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org

3.3.4.1 Great Britain Sites

3.3.4.1.1 Macroclimate

All UK Limestone pavements selected were situated within the regional climate zone of the Northwest England & Isle of Man, as designated by the Met Office (Met Office, 2016a). This zone stretches from the Scottish border in the north to the border of Cheshire and Shropshire in the south, and between the Isle of Man in the west and the Pennines in the East. The temperature of this Zone has a mean of 10.5 °C, which is similar in temperature to the warmest climate zone in Cornwall (11°C). The temperature of this zone is highly dependent on altitude, which decreases the temperature by approximately 0.5°C for each 100m of elevation. The number of hours of sunlight per day is also influenced by elevation, producing average annual sunshine durations between 1200 hours in the higher altitudes to about 1500 hours on the coast. The amplitude of seasonal and diurnal cycles in temperature are reduced with proximity to the coast resulting in higher maximum and lower minimum temperatures further inland, but retaining a similar average temperature. The warmest month occurs in July or August where temperatures reach a monthly mean temperature of between 21°C and 17°C. January is the coolest month for this zone, producing a mean temperature of around 2°C. The exposure of the Northwest Zone to westerly winds from the sea means that this zone is relatively windy. This wind brings with it maritime air masses which together with the predominance of areas of relatively high elevation results in a great deal of cloud and rain, making this one of the wettest places in the UK. Rainfall in this zone is well-distributed through the year with slightly more rain falling in winter. The average rainfall is between 3200mm/year of rain in higher elevations and 830mm/year near sea level. Flooding is not uncommon in this zone when soils reach saturation in winter and early spring (Met Office, 2016a).

3.3.4.1.2 Geology and Lithology

The sites selected for study were situated either on the Pennine range or in the foothills between the Pennines and Lake District. Each of the sites were situated on an area of Dinantian Limestone but were often surrounded by other limestone from the Yoredale Group or Silurian sandstone, conglomerate, siltstone or mudstone (British Geological Survey, 2018).

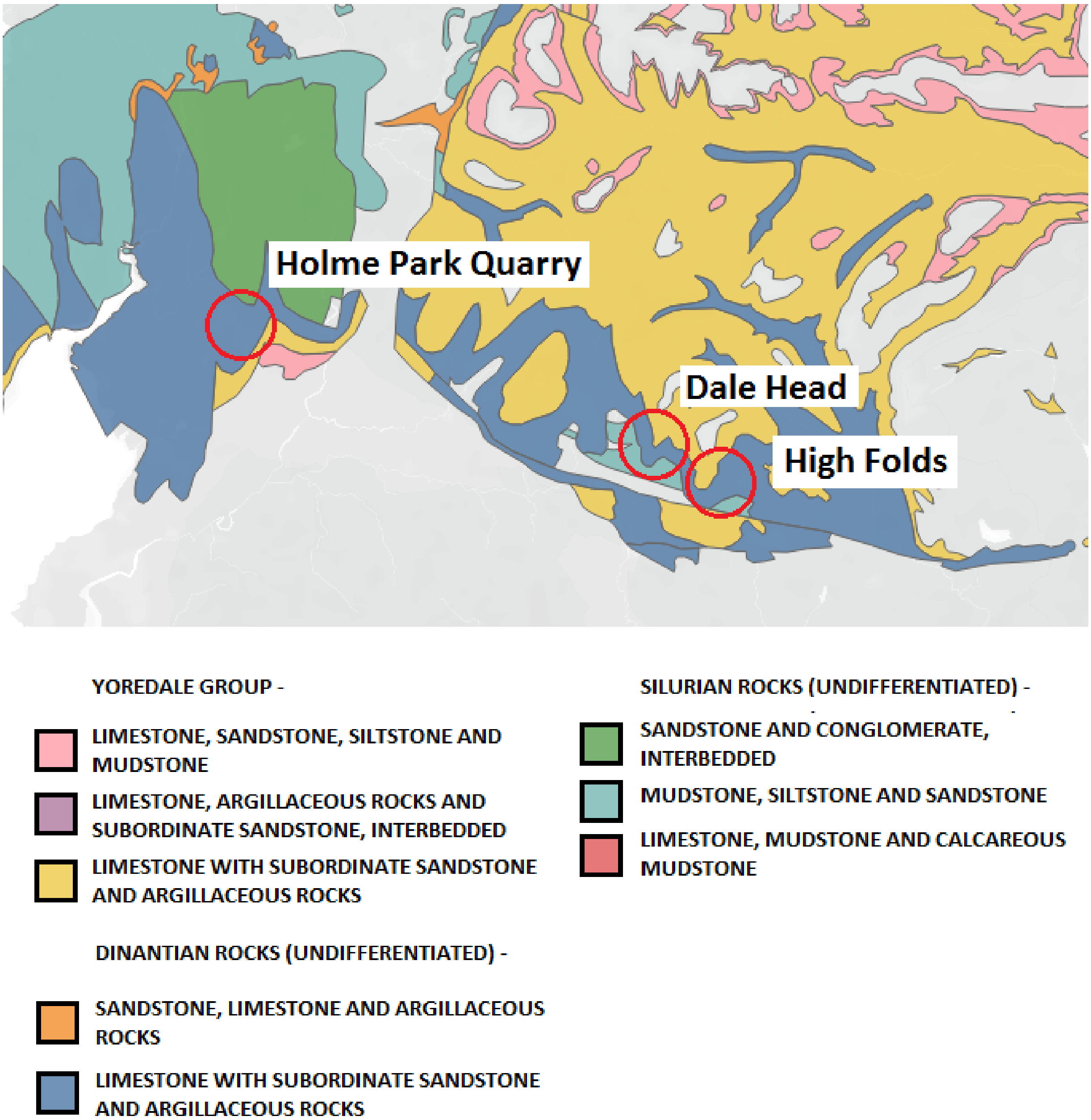


Figure 3.6 Bedrock Geology of the area surrounding the studied limestone pavements in the UK (highlighted in red) (British Geological Survey, 2018).

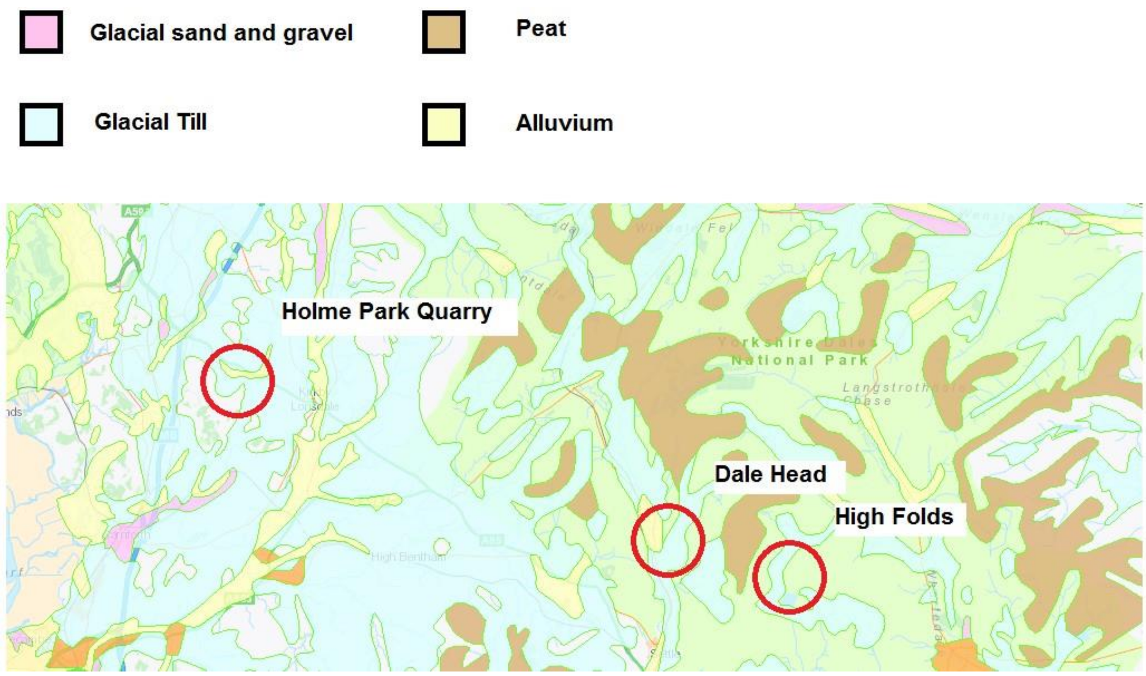


Figure 3.7 Superficial Deposits in the area surrounding the studied limestone pavements in the UK (highlighted in red) (British Geological Survey, 2018).

The surrounding area to the study sites contained a patchwork of superficial deposits made up of glacial till, sand and gravel. Patches of alluvium often surround rivers, and upland areas are frequently covered by Peat deposits (British Geological Survey, 2018).

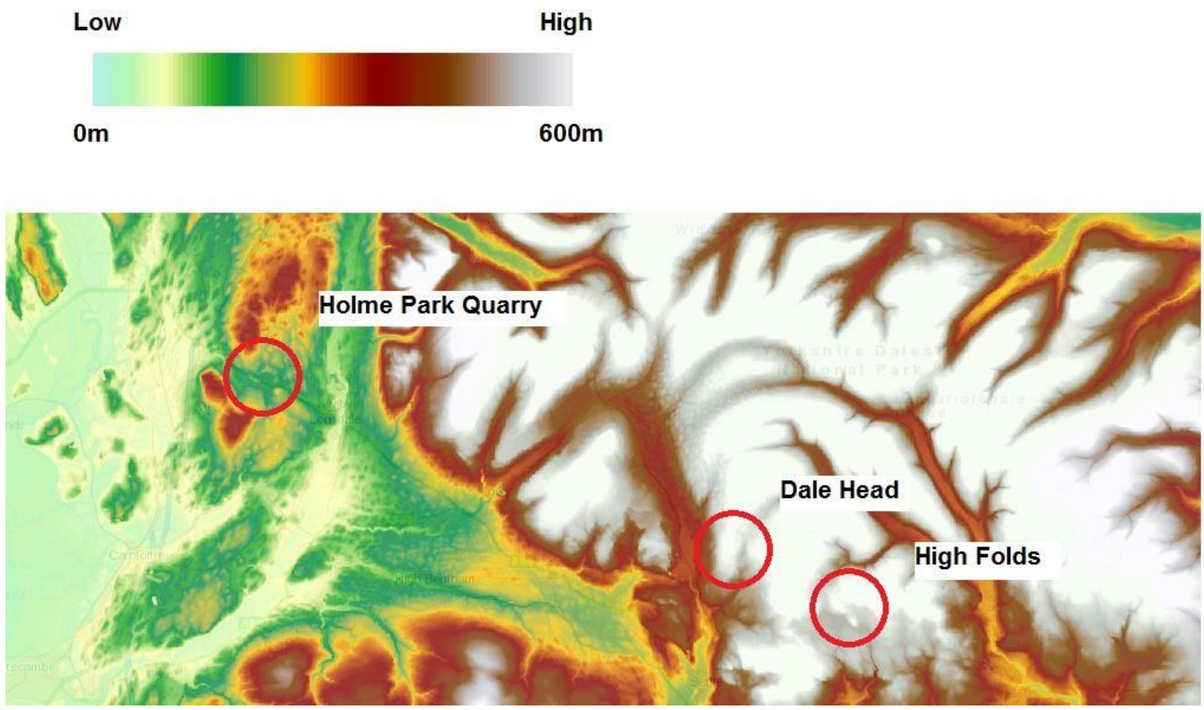


Figure 3.8 Elevation of the area surrounding the studied limestone pavements in the UK (highlighted in red) (British Geological Survey, 2018).

3.3.4.1.3 Anthropogeography and Biogeography

The valuable rocks, minerals and fossil fuels locked within the landscape of this area have resulted in a great deal of mining and quarrying surrounding the sites that were studied (Aitkenhead, 2002). Quarrying was most prominent surrounding the Holme Park Quarry limestone pavement that was surrounded by an active quarry. The peat deposits surrounding Dale Head and High Folds were used by humans until recently to fuel cooking fires and provide industry to the area. Now the peat deposits and their ecology are threatened by burning and by sheep farming to a lesser degree (Ward et al., 2007). Sheep farming has become the main agricultural industry and dominant influence on much of the uplands surrounding the limestone pavement sites (Pears, 2014). Sheep farming has come to dominate places designated as a "Less Favoured Area" which cover much of the North Pennines and Lake District (Department for Environment, Food and Rural Affairs, 2016) due to the poor productivity and relatively high elevation. In turn, sheep are then blamed for the impoverishment of moorland flora and increased erosion (Pears, 2014).

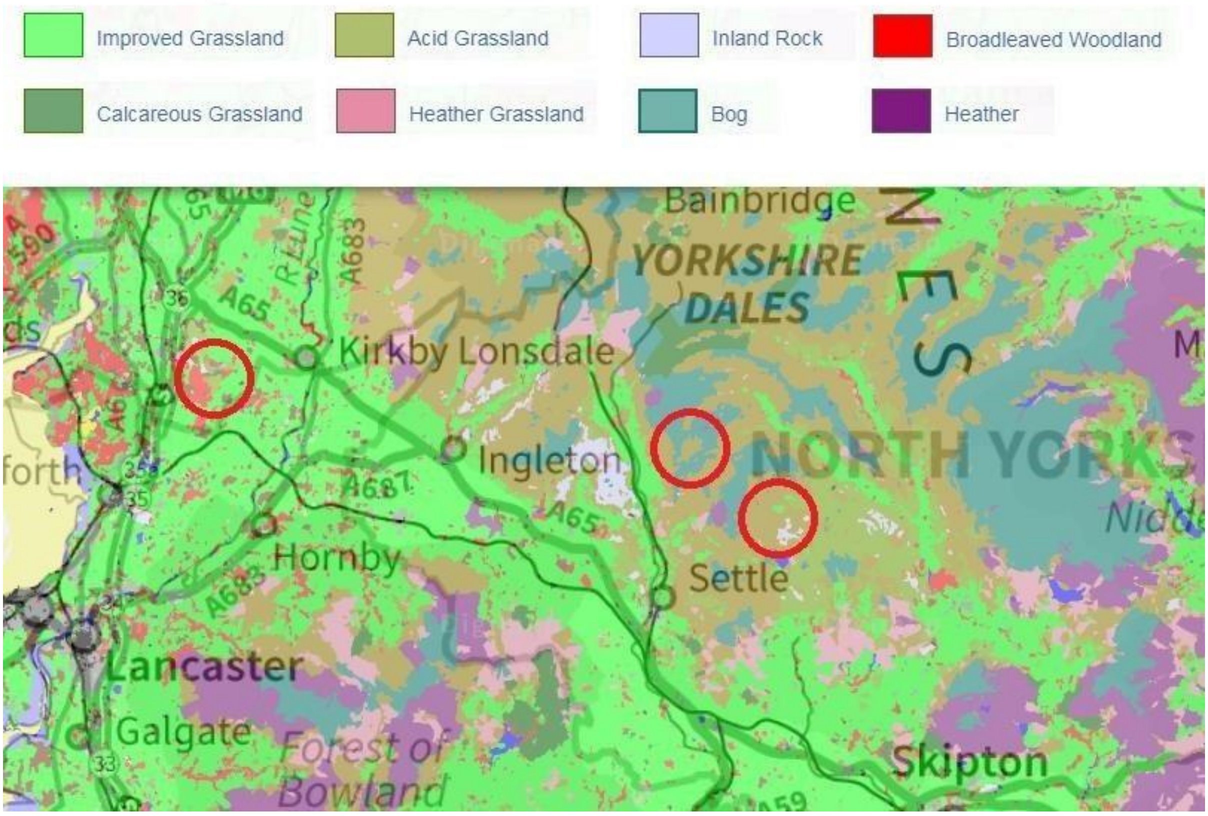


Figure 3.9 Land use of the area surrounding the studied limestone pavements in the UK (highlighted in red) (EDINA, 2015).

The interplay between the underlying geology of the region and human actions has created an environment which is maintained mainly as grassland. This grassland is largely considered "Improved Grassland", despite the calcareous underpinning or deposits of glacial till. Much of the grassland is dominated by only a small number of grasses which are characterised by their resistance to grazing (England Field Unit, 1990). Despite this dominant habitat type, there are instances of limestone flora including Spring Cinquefoil (*Potentilla neumanniana*), Bird's-eye Primrose (*Primula farinose*) and several orchid species (Joint Nature Conservation Committee, 2002).

3.3.4.2 Republic of Ireland Sites

3.3.4.2.1 Macroclimate

The temperature regime in The Burren is highly dependent on the moderating influence of the sea and elevation. The average temperature of The Burren ranges from around 10°C close to the coast to 8°C at higher elevations inland. Seasonal average temperature follows a similar distribution to the regional average temperature. In summer average temperatures may reach 16°C in July and it is often coolest in January when areas can average 8°C. Compared to areas of similar elevation in the rest of Ireland, The Burren receives a milder winter and cooler summer (Walsh, 2012).

The West Coast of Ireland receives westerly winds from the Atlantic, which increase cloud cover and rain for The Burren. The daily sunshine hours range between 1300 on the coast to only 1100 hours at higher elevations. Average rainfall over The Burren ranges from 1000mm/year near the coast to 1600mm/year at the highest elevations. The driest seasons are spring and summer where rainfall can be as little as 200mm per month in areas. Winter is the wettest season, in which high elevations can receive over 600mm per month of rain (Walsh, 2012). Owing to the distinctive geology of the region, temporary lakes which are known as Turloughs can rapidly appear when rain is especially heavy, which flood wide areas and quickly drain once the rain subsides (Marinus, 2003).

3.3.4.2.2 Geology and Lithology

The Burren is one of the largest concentrations of limestone pavements in the world and contains some of the most undisturbed specimens of limestone pavement (Monroe & Wicander, 2011). The two sites under study in the Republic of Ireland were situated within The Burren Geopark; this area is highly dominated by Carboniferous limestone with areas of Carboniferous Siltstone (Geological Survey Ireland, 2017).

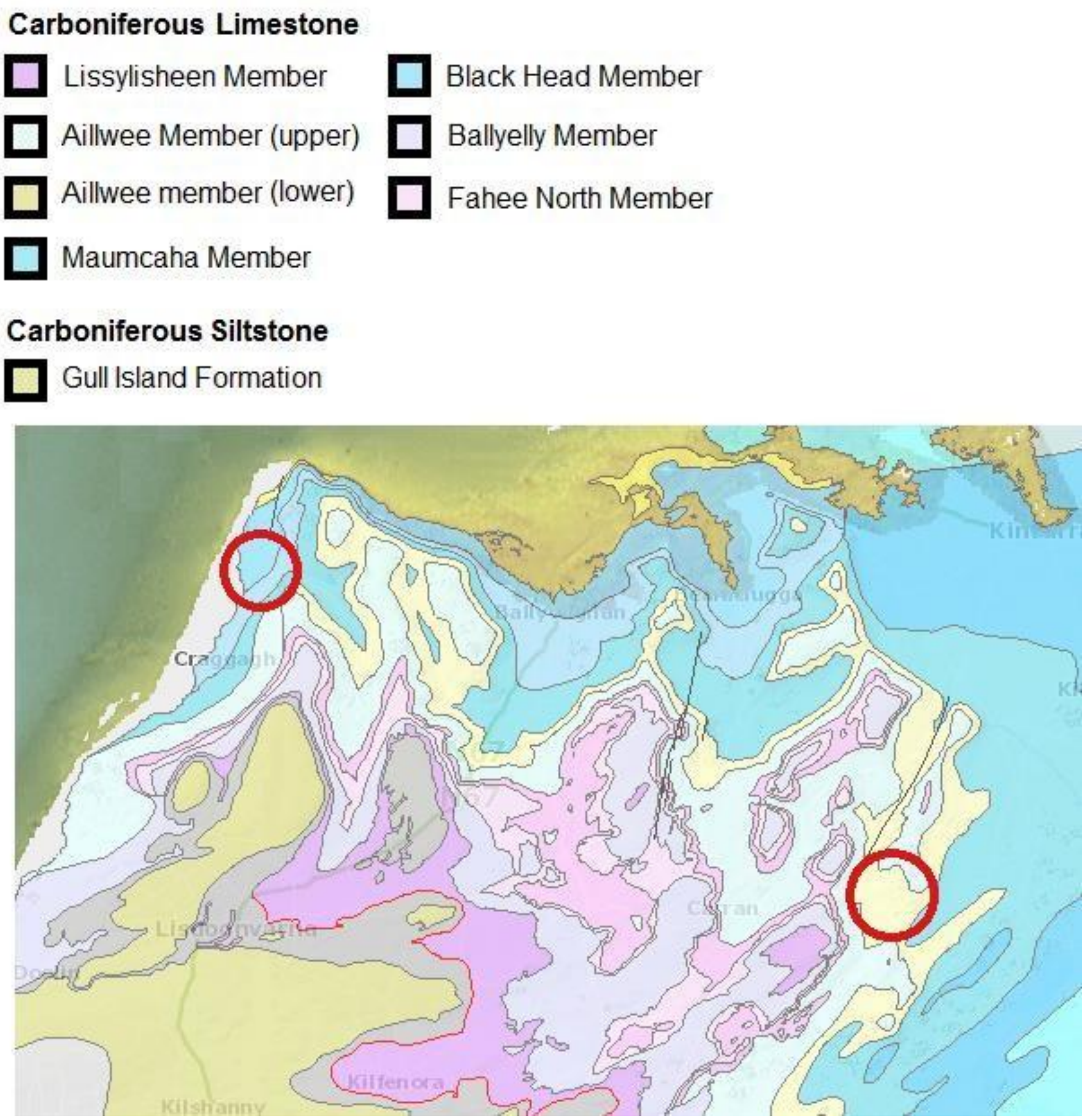


Figure 3.10 Bedrock Geology of the area surrounding the studied limestone pavements in the Republic of Ireland (highlighted in red) (Geological Survey Ireland, 2017).

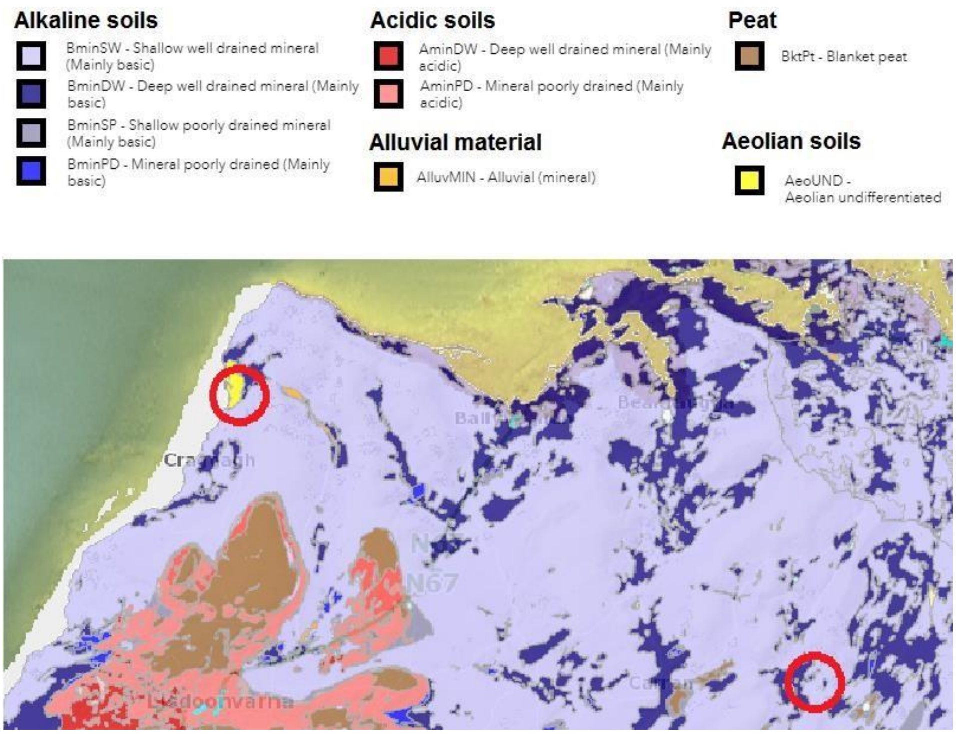


Figure 3.11 Superficial Deposits in the area surrounding the studied limestone pavements in the Republic of Ireland (highlighted in red) (Ireland, Geological Survey, 2017).

The area surrounding the sites which were studied is largely covered by superficial deposits of deep or shallow well-drained alkaline soils. In the immediate vicinity of Fanore, there are deposits of Aeolian soils which are deposited as a beach.

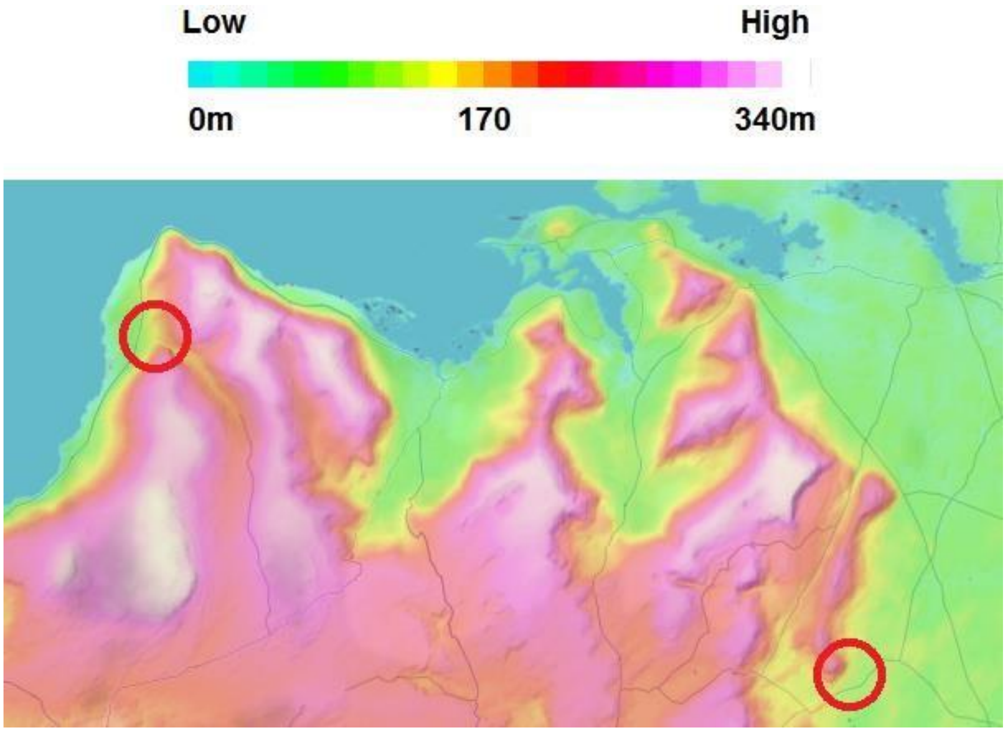


Figure 3.12 Elevation of the area surrounding the studied limestone pavements in the Republic of Ireland (highlighted in red) (Open Street Map, 2018)

3.3.4.2.3 Anthropogeography and Biogeography

The biodiversity of The Burren is as a result of both the substrate and the effect of human influences. Pollen records show that Burren was wooded by Hazel and other tree species for a period from ca. 3200-0 BP, however, during the eighteenth and nineteenth centuries these species were almost totally cleared for growing crops (Jeličić & O'Connell, 1992). Changes in land use have allowed some of the woodlands and scrub to return, hazel, in particular, has flourished due to the preference for The Burren's well-draining soils (Jeličić & O'Connell, 1992; Aalen, 1997). Today The Burren is a semi-natural environment, and the calcareous grasslands which cover much of the area around the limestone pavements are largely anthropogenic (Burrenbeo Trust, 2016). Despite "negative" human influences and perhaps aided by conservation efforts, the natural biodiversity of The Burren represents 70% of Ireland's native flora species including many rare species of orchid which thrive on the well-drained calcareous soils. In turn, the floral diversity supports a wide range of fauna. The Burren is home to all but two of Ireland's thirty butterfly species due to the wide range of food sources and relative lack of disturbance (Burrenbro Trust, 2016).

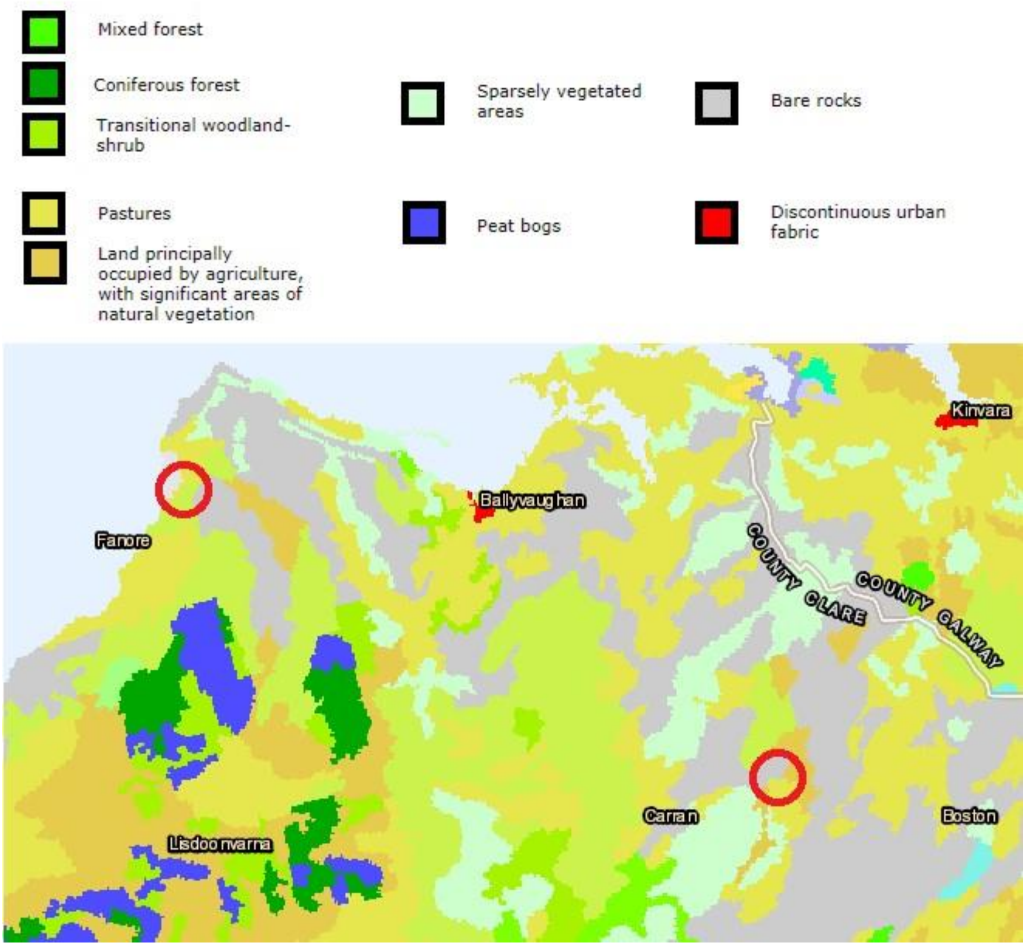


Figure 3.13 Land use of the area surrounding the studied limestone pavements in the Republic of Ireland (highlighted in red) (European Environment Agency, 2018).

3.3.5 Site summaries

3.3.5.1 Holme Park Quarry - SD538 788 (Group 3)

The Holme Park Quarry limestone pavement was distinct among the sites surveyed as it was situated on an elevated island of limestone pavement 130m above sea level, within the working Aggregate Industries owned quarry near the Cumbria village of Holme. The limestone pavement was very flat with an aspect of 241.4 with a slope of 1.82%, although as mentioned, the surrounding quarry was considerably more uneven (UKSO, 2019). The site was situated on Dinantian limestone with superficial deposits of Devensian - Diamicton glacial till (British Geological Survey, 2018). The site was included in the pavement Groups by Willis and was determined to be in Group 3 due to its situation proximal to the coast, though not as close as Fanore. The surface of the pavement was generally characterised as open; however, there were occasional ash and hawthorn trees rooted in the pavement and other smaller scrubby vegetation. The pavement was extensive and broken only by the quarry which cut the Holme Park Quarry site off from the Hutton Roof limestone pavement. Most of the grikes of the pavement were situated on the cardinal compass directions; however, in other parts of the pavement, different orientations of grike predominated. The widths of the grikes were around 20cm wide, infrequently deviating by 10cm at the most. The depth of the grikes ranged from 20cm to almost two metres, however most fell in the region of 50cm to 70 cm.

Figure 3.14 Photograph of the Holme Park Quarry Limestone Pavement (Cumbria, UK).

3.3.5.2 High Folds - SD 893 674 (Group 1)

The High Folds limestone pavement was an extensively studied site situated at 465m above sea level above the Malham Tarn Field Studies Centre in the Yorkshire Dales. The site was very flat, with an aspect of 321.95 with a slope of 5.71% (UKSO, 2019). The site was situated on Dinantian limestone with superficial deposits of Devensian - Diamicton glacial till (British Geological Survey, 2018) Surrounding sites were classified in Group 1 of Willis's Groups due to the extreme altitude of the site and lack of site vegetation. The site itself was made up of small pavements isolated from one another by tussocky limestone grassland and broken limestone. This site was distinct among limestone pavements in this survey as the direction of the grikes were 45° to the cardinal compass directions. The grikes were also shallow when compared to other grikes in this study, rarely reaching a maximum of 125 cm in places. The widths of grikes were regular at around 25 cm, rarely exceeding 10 cm above or below this figure.

Figure 3.15 Photograph of the High Folds Limestone Pavement (Yorkshire, UK).

3.3.5.3 Dale Head – SD 840 714 (Group 6)

Dale Head was situated in an extremely isolated area at 428m above sea level east of Ingleton in the Yorkshire Dales on the Pennine Way. The pavement was flat; however, the aspect of the area surrounding the site was 107.45, with a slope of 7.66% (UKSO, 2019). The site was situated on Dinantian limestone with superficial deposits of Devensian - Diamicton glacial till (British Geological Survey, 2018). This pavement was classified in Group 6 of Willis' Groups due to its thick bedding. The Dale Head grikes had a high mean depth; however, the maximum depth of grike was only 125cm. The width of grikes was regular at around 20 cm ranging only 10 cm either side on rare occasions. The Dale Head site was small and isolated from other similar sites in the surrounding area. The area surrounding the limestone pavement was open and lacking in large vegetation aside from sparse ash tree cover; however, the grikes contained a large number of floral species.

Figure 3.16 Photograph of the Dale Head Limestone Pavement (Yorkshire, UK).

3.3.5.4 Fanore – M 115 039 (Coastal)

Fanore was on the west coast of the Republic of Ireland in County Clare situated only 129m above sea level. The aspect of the surrounding area was 309.24 with a slope of 28.84%; although the pavement was extremely flat (UKSO, 2019). The site was situated on Carboniferous limestone from the Black Head member with superficial undifferentiated aeolian deposits (Geological Survey Ireland, 2017). The site was not formally categorised with Willis's Groups. However, an undergraduate dissertation survey estimated it to be Group 3 (Higgins, 2014). The proximity of the sea dominated the character of this site, which was situated under 500m from the Atlantic Ocean. The pavement was open, lacking any large vegetation and very extensive; however, it was broken into distinct areas by limestone grassland and a natural bedding plane producing a stepped terrace terrain. The grikes were orientated almost directly on the cardinal compass directions, and the width was regular, rarely exceeding 30 cm. The depth was variable depending upon the position of the grike in the pavement and depths ranged from 20 cm to as deep as three metres.

Figure 3.17 Photograph of the Fanore Limestone Pavement (The Burren, Republic of Ireland).

3.3.5.5 Turlough More - R 333 986 (inland)

The Turlough More site was situated at 90m above sea level toward the interior of the west coast of the Republic of Ireland near the town of Gort in County Clare. The aspect of the surrounding site was 145.57, with a slope of 24.28%, though the pavement was very flat (UKSO, 2019). The site was situated on Carboniferous limestone from the Lower Aillwee member with superficial, shallow and well-drained material derived from the surrounding rock (Geological Survey Ireland, 2017). As with Fanore, this site was not formally categorised by Willis's 2011 survey. However, it was later estimated to be Group 1 or 3 (Higgins, 2014). The dominant characteristic of the Turlough More site was that of extreme depth. The grikes situated on the pavement were frequently over 1.5 m in depth, and many grikes reached four metres deep in parts. The width was more variable than other sites, and some grikes were 50 cm wide in places. Some grikes descended at an angle of between 5° to 10°, and all were orientated on the cardinal compass directions. The pavement itself was open with low lying blackthorn and hazel scrub, very extensive and broken only by cliff-like terraces.

Figure 3.18 Photograph of the Turlough More Limestone Pavement (The Burren, Republic of Ireland).

4. Microclimate Measurement

4.1 Introduction

Microclimates often provide a largely stabilising influence upon the changeable external climate, and the influence of grikes is no exception (Heslop-Harrison, 1960; Geiger, Aron & Todhunter, 2009). Despite receiving several short term investigations detailed in the literature review in Chapter Two, the grike microclimate has not yet received any suitably long-term study from which to simulate a set of possible future grike microclimate temperatures over all seasons. Microclimate was rarely the main focus of the past investigations in which it was a feature. In early studies that included an element of microclimate measurement, the focus was on flora and fauna of this habitat (Phillips, 1910; Webb, 1947). The small amount of research focusing on microclimate has been limited to a small number of studies over a period of only fifty years, from the 1960s (Heslop-Harrison, 1960 Dickinson et al., 1964; Yarranton & Beasleigh, 1968 & 1969) with little further research conducted until the late 1990s and 2000s (Burek & Legg, 1999; Alexander, Burek & Gibbs, 2007). The conclusions of these studies are detailed in Subsection 2.2 of the literature review of this thesis.

A key topic within this chapter is the stability of the grike microclimate, which is hypothesised to be key to the "unique plant community which characterises the microclimates of the grikes" (Willis, 2011). Temperature stabilisation within microclimates is also hypothesised to be one of the key defences of refugia and microrefugia against the periodic temperature extremes predicted during climate change (Suggitt et al., 2011; Hannah et al., 2014). It is for this reason that it is important to understand the effect of the form and position of a grike on the microclimate found within and to do so over an extended period.

This chapter includes part of the research undertaken as part of Phase One of the methodological research structure. The introduction to this thesis highlights the importance of the long-term study of the grike microclimate in Subsection 1.2.1. Here it is specified that the microclimate of the grike should be studied for over a year in order to understand the periodic nature of variables. These produce data with which to simulate the temperature and understand the nuances and tolerances of the stabilising effect. This chapter aims to achieve the third objective of this thesis and provide the groundwork upon which further data analysis and simulation can be based.

4.2 Methodology

4.2.1 Grike Selection

Site selection is detailed in Subsections 3.3.2. Subsections 3.3.1 and 3.3.3 discuss Willis's Groups. These subsections also include the limitations of using this as a basis for site selection and the measures that were taken to select a subset of representative and secure pavements likely to contain grikes for study. The choice of the grikes on each limestone pavement was based upon several further criteria outlined in Table 4.1.

Table 4.1 Rules for the choice of limestone pavement grikes used as part of the grike selection methodology.

Rule	Reason
Grikes must represent the Willis Group of the pavement on which they are situated (Willis, 2011) or the pavement type in the case of the pavements on The Burren	The grike chosen to represent each Willis Group must present characteristics typical of that pavement to ensure a representative range of pavements.
Grikes must be orientated on the cardinal compass directions; however, should any pavement be suitable in all other respects grikes orientated 45° from a cardinal compass direction were accepted.	Preference was given to grikes on the cardinal compass directions because these are the most common in the UK (Jennings, 1985), have a precedent in limestone pavement grike literature (Burek &Legg, 1999) and allow for a comparison of the influence of solar angle on grike microclimate.
Grikes must not be situated close to a feature likely to influence the microclimate. Including human-made structures, or cliff faces shading the grike or where the grike opens onto a cliff face.	External features that influence the grike microclimate obscure the influence of the grike on microclimate.
Grikes must be hidden from the closest public thoroughfare	This was done in order to reduce the chance of data loggers being removed from the site by a malicious or misguided member of the public, where possible grikes were chosen far away from areas frequented by the general public.

Two grikes were chosen from each site which fit the criteria in Table 4.1, one grike orientated North to South (NS), and another orientated East to West (EW), replicating prior study by Burek and Legg (1999). Table 4.2 contains the measurements from the grikes used in this study.

Table 4.2 Depth, width and orientation of grikes under study.

Measurement	Holme Park Quarry		Dale Head		High Folds		Fanore				Turlough More			
Orientation	NS	EW	NS	EW	NW-SE	NE-SW	NS1	NS2	NS1	EW2	NS1	NS2	NS1	EW2
Depth (cm)	175	175	125	125	125	125	200	300	200	200	300	400	300	300
Width (cm)	18	20	24	23	21	17	24	26	25	20	28	28	29	28

4.2.2 Data Collection

When reviewing the literature on the topic of microclimate measurement in other habitats, it is common to find multiple measurements of microclimate being taken collectively over an extended period, using modern data gathering techniques to gain a broad picture of the habitat. This type of research is exemplified in caves, where temperature and relative humidity are sampled together due to the effect both variables can have on biodiversity (Paksuz, Özkan & Postawa, 2007, Pellegrini & Ferreira, 2016). In street canyons, light and temperature (Ali-Toudert & Mayer, 2006) or airflow and temperature (Xie, Liu & Leung, 2007) are sampled or modelled together to quantify the effect that outside influence has on thermal comfort in the street canyon. In limestone pavement grikes temperature, light intensity and relative humidity have been sampled together in both Canada by Yarranton and Beasleigh (1968) and on The Burren by Dickinson, Pearson and Webb (1963). To emulate prior studies and to fully understand the grike microclimate as a whole, this study needed to unify the many different influences that the macroclimate has on the grike microclimate over a long period, using automated and precise sample methods. The resultant field-based research method presented in this chapter partially fulfils the first aim of the study and provides a body of microclimate data for use in the further study of grike habitats to fulfil the second aim.

Existing studies of grike microclimates and other similar microclimates were examined closely before the creation of this methodology. Each grike microclimate study was at the forefront of scientific endeavour, for that particular era. However, modern microclimate measurement and data storage technology allows for greater precision and quantity of data to be gathered. In previous studies of the grike microclimate (Dickinson, Pearson & Webb, 1964; Silvertown, 1982; Burek & Legg, 1999) a reliance on manual data collection resulted in short study periods which could not account for seasonality of microclimate or capture a wide breadth of conditions from which to make conclusions.

In the field of cave microclimate research, improved data collection technologies have allowed for the on-going collection of cave temperature data in Scoska Cave since 2006 (Hodgson, 2009). Similarly, more recent microclimatic studies of the grike have used automated data collection, however, due to difficulties with the reliability of equipment some data were lost (Alexander, Burek & Gibbs, 2007) Additionally, most of the work conducted on grike microclimates has accounted for only one or two measures, focusing mainly on the temperature fluctuations observed with depth into a grike. Many recent urban microclimate studies account for the need for a multivariate approach to measurement to allow models to become a more accurate representation of the real-world scenarios which they can now simulate (Eliasson, 1996; Arnfield, 2003).

Based on the methodological literature available, the approach for this study was able to establish a robust long-term record of the microclimate of grikes, using modern climate capture and data logging technologies, collecting a range of climatological variables.

4.2.2.1 Prior considerations

When considering the requirements for an extended investigation on limestone pavements, multiple factors need to be evaluated.

- All English limestone pavements are subject to Limestone Pavement Orders (LPOs) "prohibiting the removal or disturbance of limestone" on the site with a penalty of up to £20,000 for an offence. Many Limestone pavements are also designated as SSSIs (Site of Special Scientific Interest), placing a further maximum fine of £20,000 for any damage to the habitat (Wildlife and Countryside Act, 1981; Countryside and Rights of Way Act, 2000). Further protection is afforded to Limestone Pavements in both Great Britain and the Republic of Ireland through Natura 2000 (Council of the European Commission, 1992). This network designates many limestone pavements as Special Areas of Conservation (SACs) where all extraction or damage to limestone pavements is illegal. In the Republic of Ireland, 40 limestone pavement sites have been designated as SACs, three of which protect 28,503ha of The Burren (Irish Wildlife Trust, 2008).
- For the study to be cost-effective, the data storage capacity of all data loggers would be of high priority. Larger storage capacity reduced the frequency of data collection visits; however, the over-long spacing between collections may have led to the danger of any hardware malfunctions remaining undiscovered and valuable data being lost. For this reason, a compromise was considered.
- In order to have as little impact on the limestone pavement habitat as possible disturbance limitation measures were taken and detailed in Subsection 4.2.3.3.

4.2.2.2 Measurements considered

Our understanding of the climate of an area is based upon the meteorological measurement of temperature, humidity, pressure, evapotranspiration, light intensity, wind-speed and precipitation (Geiger, Aron & Todhunter, 2009). In order to measure the microclimate of a grike, measurements of temperature, relative humidity and light intensity were collected from within the grike and from the grike surface. Air pressure was excluded from the measurements taken. This was because on a small scale; air pressure was not a cost-effective parameter to consider. Although Hoyos et al., (1998) consider air pressure to be a valuable predictor of cave microclimate; this parameter has not been as widely reported as relative humidity, light or temperature. The equipment used to measure air pressure was found by the author to be three times more expensive than any other microclimate data logging probe. Evapotranspiration was not measured because it requires either a closed system for the water balance of basin and porometry, a more regular site presence than is possible for evaporation pan lysimetry and soil moisture depletion or is conducted on a macroclimate scale using a Scintillometer or Lidar (Shuttleworth, 2008). Measurement of airflow from within a grike was not possible, as the anemometers required were found to be too bulky and may have influenced airflow being measured. In Chapter Five, airflow was simulated using Computational Fluid Dynamics (CFD) to replace direct measurement.

The gas composition of the air surrounding invertebrate species found in a grike is highly influential on their homeostasis, and the efficacy of gas exchange is affected by relative humidity (Johnson, 2017). However, it was decided that atmospheric composition fell outside of the definition of a microclimate, and was therefore not suitable for study in this project. Study of the variation in the air within a grike could, however, provide information equally beneficial to grike conservation and microclimate research and should be considered for future study.

4.2.2.3 Measurements taken

4.2.2.3.1 Temperature

Temperature measurement was recorded using the HOBO Pendant Temp/Light Logger and the ELUSB-2 Humidity & Temperature USB data logger within the grike. The temperature was measured because it has a precedent in grike microclimate research and is the most commonly recorded microclimatic variable in limestone pavements (Heslop-Harrison, 1960; Dickinson, Pearson & Webb, 1964; Silvertown, 1982; Burek & Legg, 1999; Alexander, Burek, & Gibbs, 2007) and is considered the most important climatic factor for studying plants and animals (Stoutjesdijk & Barkman, 2014). Most terrestrial invertebrates are ectotherms and therefore rely heavily on a stable range of temperatures for normal levels of behaviour (Chown & Nicolson, 2004). As a general rule, it has been observed that as temperature rises, the activity of the invertebrate increases until a critical level is reached at which it dies (Lutterschmidt & Hutchison, 1997; Chown, 2001). For example, higher temperatures have been observed to decrease the time taken for insects to develop, resulting in a smaller body size overall (Atkinson & Sibly, 1997). The importance of temperature to invertebrate function is discussed in greater detail in Subsection 7.1.1.

4.2.2.3.2 Relative humidity

Relative humidity measurements have been taken using EL-USB-2 Humidity & Temperature USB data loggers within the grike. There are three potential measures of humidity used in climate studies:

- Absolute humidity – the total mass of water vapour contained in a given volume/mass of air
- Specific humidity – the total mass of water vapour within a given volume of air, expressed as a ratio of vapour to air.
- Relative humidity – the amount of water vapour in the air as a percentage of the potential maximum humidity for the specific air temperature.

(Barry & Hall-McKim, 2014)

On the scale used in relative humidity, 100% is air saturated to the point where water may no longer evaporate into it, and 0% relative humidity is air with no water content. Warmer air has a higher capacity to hold water, and as it cools, the air with 100% relative humidity will result in condensation and remain at 100% relative humidity (Barry & Hall-McKim, 2014). Relative humidity was chosen as the most applicable measurement for this study because it has an established history of being collected in grikes (Heslop-Harrison, 1960; Dickinson, Pearson & Webb, 1964; Burek & Legg, 1999; Alexander, Burek, & Gibbs, 2007). By maintaining established metrics, it is possible to make comparisons between this study and past studies.

Although it is less commonly measured than temperature or light, relative humidity is very important to understanding the microclimate (Stoutjesdijk & Barkman, 2014) and in particular, relative humidity has direct application to evapotranspiration in plants and moisture retention in invertebrates (Stoutjesdijk & Barkman, 2014; Jones, 1993). The effect of relative humidity on the action of insects is far less studied than temperature; however, there is evidence to suggest that it can be a major determinant of activity (Raghu, Drew & Clarke, 2004). Should the greater number of high precipitation events increase as predicted (Jenkins et al., 2009) the relative humidity of the grike may remain high for longer periods. More available water may impact the biodiversity by encouraging different floral species to inhabit the grike, impacting the microclimate of the grike in unpredictable ways.

Figure 4.1 Dataloggers used in this study. EL-USB-2 Humidity & Temperature USB data logger (Left) and HOBO Pendant Temp/Light Logger (Right).

4.2.2.3.3 Light intensity

Light intensity measurements have been taken using the HOBO Pendant Temp/Light Logger within the grike and on the surface. Light intensity is the least well researched of the measurements of microclimate taken from within grikes (Dickinson, Pearson & Webb, 1964; Alexander, Burek, & Gibbs, 2007). Light intensity, however, has large implications for the amount of heat radiation received by basking insects and on the air temperature of microclimates in which invertebrates live (Schultz, 1998; Burek & Legg, 1999). Light levels are also important to plants for photosynthesis and for insects for maintaining circadian rhythms, even in low light environments (Jones, 2013; Lazzari, 1992).

4.2.2.3.4 Other considerations

Data loggers used for this study were primarily chosen for their physical size. The methodology for recording grike microclimate data used by Alexander, Burek and Gibbs (2007) identifies that loggers should not touch the sides of a grike in order to ensure only the temperature of the atmosphere is collected. Grikes observed in previous studies (Willis, 2011) have been over a metre in width when measured from the surface; however, grikes often quickly get narrower as they get deeper. In order to ensure that equipment can operate in most grikes, data loggers must be able to fit in a grike space and collect their intended variable. Whilst ensuring that light logger sensors must face upward and temperature loggers must not touch grike walls.

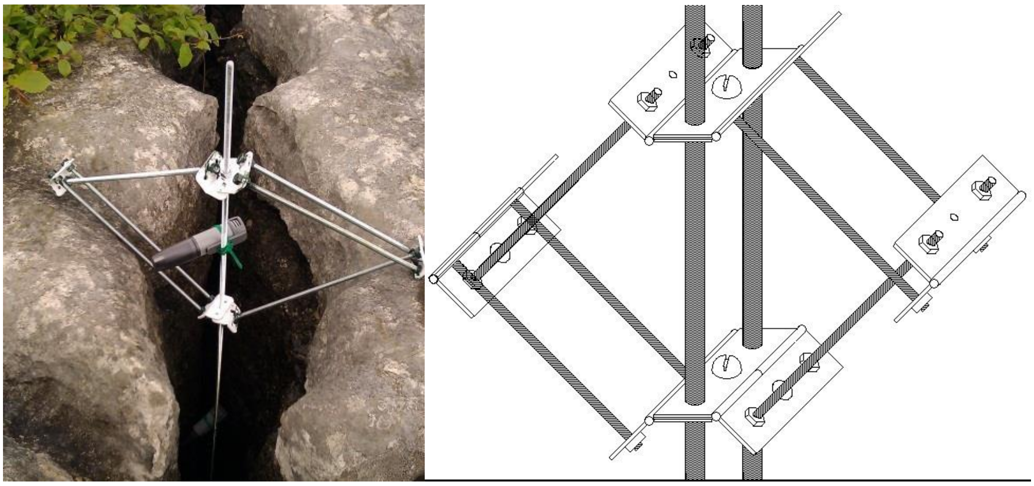


Figure 4.2 Data loggers in situ on the Holme Park Quarry limestone pavement (left), an illustration of expanding hinges (right) (Cumbria, UK).

The data loggers were suspended within the grike such that they did not move from the centre of the grike during or between measurements. Loggers had no contact with the grike walls, and the structure used to suspend loggers did not interfere with the measurements. Previous studies of limestone pavement grike microclimate have secured sensors in place using a structure of uPVC plumbing piping. This structure both provided structure and protected the wires from damage by rabbits (Alexander, Burek & Gibbs, 2007). The current study used integrated sensor data logger technology and therefore did not need bulky pipes which may have interfered with air passage and block light. Instead, an aluminium metal rod was used and secured in place using a series of expanding hinges, capable of exerting pressure on the grike walls (Figure 4.2). This housing provided a structure for the data loggers without interfering with the data collected.

4.2.3 Procedure

4.2.3.1 Data capture timetable

Fieldwork for this project took place from May 2011 to August 2016 to make the effective use of the resources available and allow time for detailed long-term study of multiple limestone pavement grikes. This research aimed to capture the character of the grike microclimate over all four seasons. In order to collect enough data to make a robust case for the individuality of the grike microclimate, data collection for each site took place over at least two years. The extended period over which data were gathered decreased the chance of data sets being skewed by a year with abnormal weather patterns as occurred in the grike microclimate study conducted by Silvertown (1982) where the temperature was abnormally high during the entire year of study.

In actuality, microclimate data was collected from the limestone pavements under study for the following durations.

Holme Park Quarry:	From 27/06/2011 to 13/08/2016, 5 years, 1 month, 17 days
Dale Head:	From 02/12/2011 to 27/12/2013, 2 years, 25 days
High Folds:	From 01/12/2011 to 01/07/2016, 4 years, 7 months
Fanore:	From 15/09/2012 to 07/02/2015, 2 years, 4 months, 23 days
Turlough More:	From 15/09/2012 to 07/11/2014, 2 years, 1 month, 23 days

4.2.3.2 Installation

Once a grike had been selected using the methodology detailed above, the data loggers were installed in order to collect the data. All data loggers were initiated, given unique reference numbers and primed to begin logging simultaneously at midnight on the date of installation. The logging frequency was set at a one-hour interval. This rate was deemed frequent enough to be sensitive to mild daily fluctuations in temperature, but not too frequent as to produce too much data for processing or to risk the memory of the logger. Hourly readings have also become standard in microclimate studies of this type (Silvertown, 1982).

Each logger was placed on the logger pole (Figure 4.2). At the surface, a relative humidity and temperature logger was positioned at the top of the EW grike, and a light and temperature logger was positioned at the top of the NS grike. Between the surface and 200cm, both grikes collected the same microclimatic variables at the same intervals. Starting at 25cm light and temperature loggers were placed at intervals of 50cm (e.g., 25cm, 75cm, 125 cm, 175cm) and starting at 50cm relative humidity and temperature loggers were placed at intervals of 50cm (50cm, 100cm, 150cm). At 200cm, at each metre below 200cm and at the base of each grike, both loggers were used to collect all variables. The poles were then inserted into each grike, and the hinged bracing was extended to ensure the pole did not move inside the grike.

Once initiated, the data was collected by visiting the site every three months. A prior study of the grike microclimate using a similar apparatus was curtailed due to faults with the equipment (Alexander, Burek & Gibbs, 2007). It is not clear how frequently data loggers were checked from the published methodology; however, it is described that 17 months of data were lost. In order to avoid lost data, a three-month interval in data collection was decided to be the most cost-effective while also limiting the effect of any disturbance or fault. Collecting the data was completed by loosening the bracing and removing the pole from the grike. The time was checked before disturbing the loggers, and if the time was fewer than 15 minutes to the hour, the removal of the pole was postponed until that hours log had been completed. Once out of the grike each data logger was stopped, data recorded and the logger restarted to begin logging again upon the next full hour.

4.2.3.3 Limiting disturbance

In order to limit disturbance to the sites under study, fieldwork was conducted following the DEFRA "Joint Code of Practice for Research" as well as the International Union for Conservation of Nature (IUCN) guidance for "responsible research and monitoring in the protected area" (Hockings et al., 2013; Department for Environment, Food and Rural Affairs, 2015). Further guidance was requested from the National Parks & Wildlife Service in the Republic of Ireland; however, a response was not provided. In order to comply with this guidance, permissions were gained from landowners in order to conduct fieldwork on each site. Precautionary measures were taken in order not to introduce "invasive" species on to any of the sites by washing boots before data collections and visual checks of clothing for burrs or adhering seeds. Disturbance to the site was kept to a minimum by standing only on the clint surfaces when traversing the limestone pavement and ensuring that solution pans with fragile edges were left intact. When crossing grasses between the pavements, care was taken to avoid fragile herbaceous plants. Care was also taken to vary the path taken when conducting visits in order to limit the trampling damage and soil erosion possibilities. No items were left on site unless necessary for the fieldwork for this study. Data collection instrumentation left on the site was inconspicuous so as not to damage the aesthetic value of the limestone pavement.

4.2.4 Analysis

Variation between sites – the benefits of conducting a long term study over multiple sites were analysed using descriptive statistics and boxplots, in order to identify the differences between the sites under study.

Temperature stability – the stability of the grike microclimate was analysed by initially comparing the current data set to prior studies using descriptive plots. The stability of the grike was then further investigated by illustrating the rate at which temperature increased and decreased within the grike. Dynamic time warping was then applied to the data using the R package “dwt” to illustrate the delay after which temperature changes in the grike when compared to the surface (Giorgino, 2015). Dynamic time warping is a process used in electronic signal manipulation to illustrate the time difference between two signals (Berndt & Clifford, 1994). To the knowledge of the author, this is a new technique to grike microclimate research. These descriptive plots of grike stability allow a greater understanding of the grike microclimate and may point toward the outside forces which cause disturbance within the grike. The variation in grike temperature has then been illustrated over a day by several studies. To the author’s knowledge, this is the first time it has been possible to plot the temperature in the grike over a year. This subsection further discusses the stability of grike temperature aided by boxplots of the cycles in the grike temperature and how they interact with grike orientation. This greater knowledge of the grike temperature provides foundations on which to base further microclimatic simulation.

Radiative heating in the grike – following on from the work of Burek and Legg (1999), and Alexander Burek and Gibbs (2007); this subsection illustrates the difference in grike temperature between NS and EW grikes using boxplots. The multiyear, multivariable data set available to this study allows the difference in both temperature and light intensity in NS and EW grikes to be observed over multiple time scales and analysed using scatter plots and plots of the Spearman’s rank correlation. The light within a grike was then simulated in order to understand how the movement of the sun influences light intensity within a grike and what hypothetically causes the differences in microclimate observed in different grike orientations.

Relative humidity – Relative humidity was investigated using boxplots in order to understand how seasonal and diurnal cycles impacted grikes at different depths and orientation.

Severe weather – Undertaking data collection for a long period allowed for natural experiments to occur in the form of severe weather events.

For the purposes of this study, periods of severe weather were those considered by the Met Office as "weather Events" or by Met Éireann as "Major Weather Events". Weather events are considered severe based on the high level of disruption they presented to transport, utilities, buildings and life by the Met Office (2019); whereas, Met Éireann consider major weather events to have been "rare and very dangerous weather conditions from intense meteorological phenomena" (2019).

Data were averaged over 24 hours in order to present the trends in the data more clearly without excessive noise. Line plots of the mean temperature taken from the months surrounding the event, illustrated the behaviour of the grike microclimate during periods of severe cold, heat and precipitation. Understanding such events is of increasing importance as they are predicted to occur on a more regular basis (Pachauri et al., 2014).

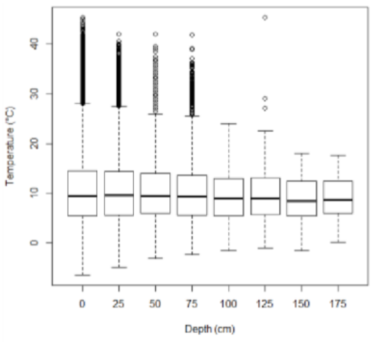
4.3 Results and Discussion

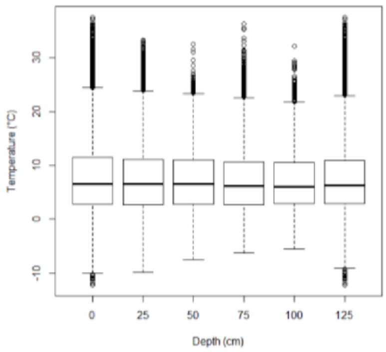
4.3.1 Variation between sites

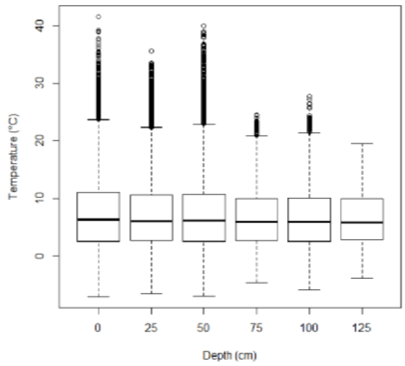
The data collection took place on several different sites with varying geographic and topographic features. These range from the highly coastal site of Fanore to the high altitude inland sites of High Folds and Dale Head. The number of sites makes it possible to compare and contrast the data, and effectively establish the impacts on microclimate caused by the site's situation.

<u>4.3.1.1 Temperature</u>

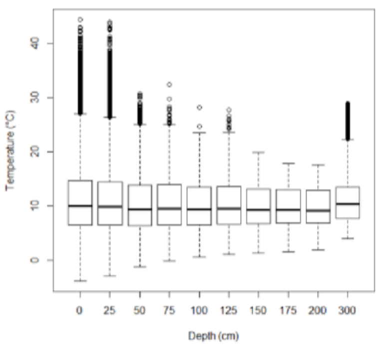
Figure 4.3 shows that the temperature data collected from each pavement was extremely similar. All the sites had a similar median temperature and a similar temperature variation. The boxplots show that Dale Head and High Folds had a lower temperature recorded from the surface and within the grikes when compared to the other sites; however, this may be expected as these sites were the highest in altitude and experience a cooler climate (Met Office, 2016a). Although the median temperature of the grike was impacted by the site, there was a very similar pattern to the data as the depth of the measurement increased.

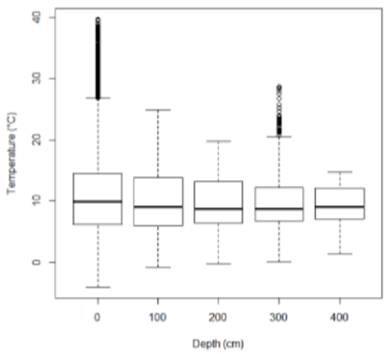






a) Holme Park Quarry b) Dale Head c) High Folds





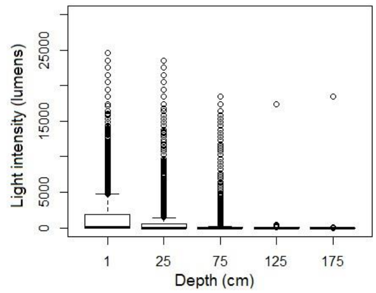
d)

Fanore e) Turlough More

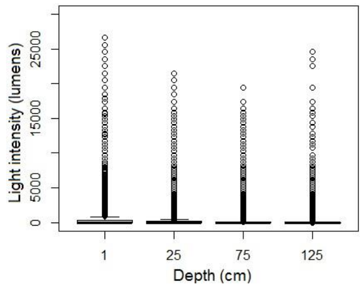
Figure 4.3 Boxplots showing the spread of temperature data from all depths in the different sites used in this study.

4.3.1.2 Light intensity

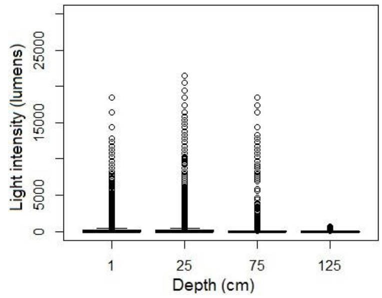
The light intensity in all sites diminished with depth until almost no light was recorded at the bottom of the deepest grikes. The rate at which light intensity decreased appeared to be dependent on the site. Both Dale Head and Fanore recorded a larger number of high light intensity outliers at a depth of 125cm than any other site. These outliers may have been due to the shape of the grike as the walls of the grike were not regular and may have provided a lesser or greater degree of shade depending on the grikes internal dimensions.



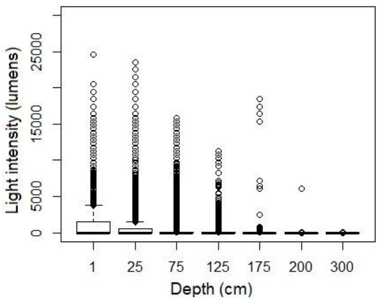
(a) Holme Park Quarry



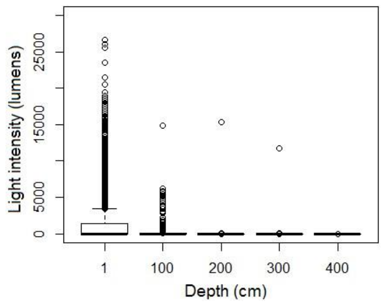
(b) Dale Head



(c) High Folds



(d) Fanore

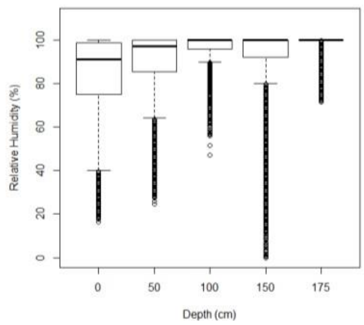


(e) Turlough More

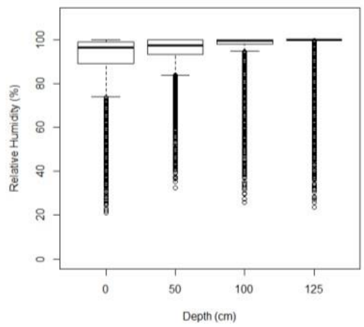
Figure 4.4 Boxplots showing the distribution of light intensity data in the different sites used in this study.

4.3.1.3 Relative humidity

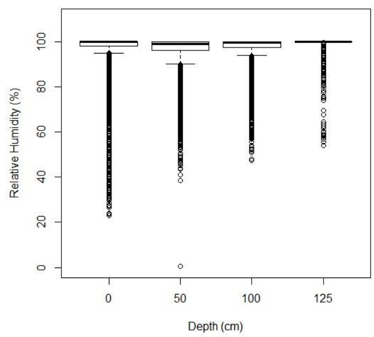
In order to identify any differences between sites, the relationship between relative humidity and depth was plotted in figure 4.5. Relative humidity appeared to increase with depth to a point where 100% relative humidity was reached almost constantly. This point was reached more rapidly in Dale Head and High Folds. The increased relative humidity on shallower grikes may highlight the importance of substrates found at the bottom of grikes in maintaining grike relative humidity; however, the higher altitude of these two sites may also have influenced the precipitation of the site thereby affecting the relative humidity (Met Office, 2016a).



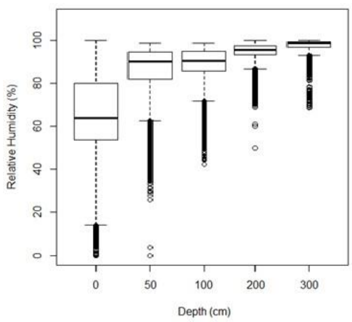
(a) Holme Park Quarry



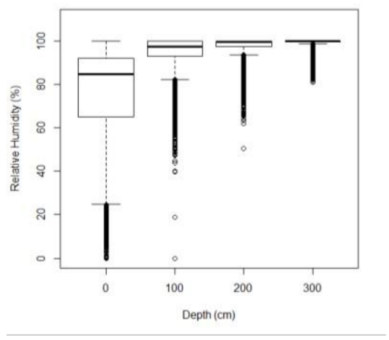
(b) Dale Head



(c) High Folds



(d) Fanore



(e) Turlough More

Figure 4.5 Boxplots showing the distribution of relative humidity data in the different sites used in this study.

4.3.1.4 Subsection conclusions

As the depth increased, the light intensity decreased and that temperature became more stable. Relative humidity also increased with distance from the surface; however, there was also a rapid increase in relative humidity toward the base of the grike. This was also found by Yarranton & Beasleigh (1969) in deeper grikes in Canada. This subsection has shown that although the sites may have their distinctive characteristics as shown by the small variations in all of the metrics collected, the underlying microclimate remained relatively unchanged.

4.3.2 Temperature stability within the grike

4.3.2.1 There is greater stability of microclimate inside a grike compared to outside a grike

Stability of microclimate was one of the first aspects of the grike microclimate to be recognised (Phillips, 1910). This stability is the key tenet of microrefugia survival, as without a stabilising influence, microrefugia microclimate change in line with the external climate (Hannah et al., 2014). Previous studies of grike microclimate have shown that the temperature is more stable inside a grike when compared to the outside and much more like a forest microclimate (Dickinson, Pearson & Webb, 1964; Ward & Evans, 1976). Dickinson, Pearson and Webb's (1964) study of The Burren limestone pavement grikes has illustrated the stability of the grike microclimate, by showing that over a day the rise and fall of temperature in a grike was reduced noticeably by depth (Figure 4.6)

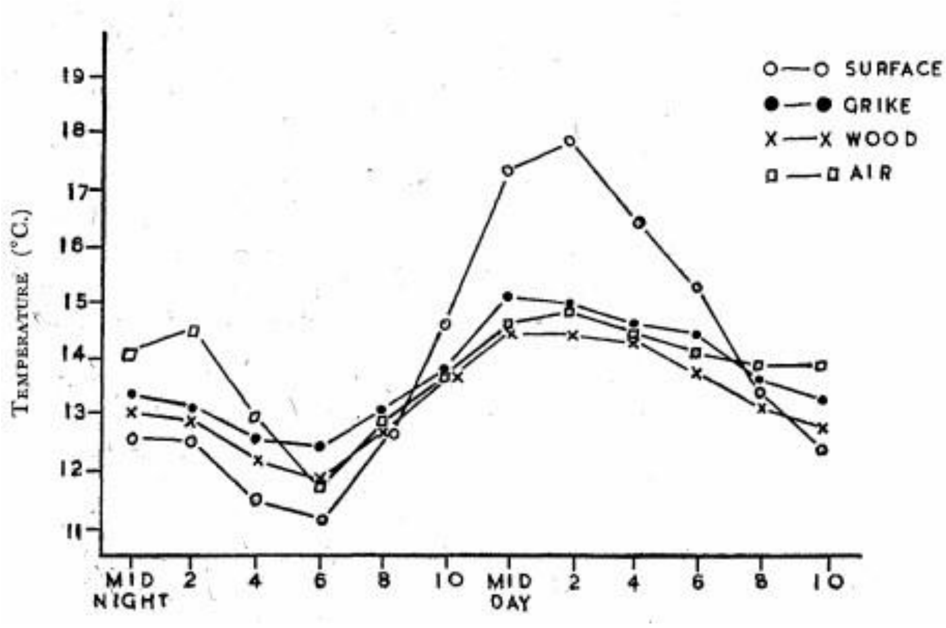


Figure 4.6 Temperature taken from a grike in The Burren and from the surrounding environments (Dickinson, Pearson & Webb, 1964).

With the data available to this study, it was possible to show that, as depth increased the temperature reacted in the way expected by previous studies (Figure 4.7). However, using the large amount of data available, it was possible to explore the grike temperature stability in greater detail.

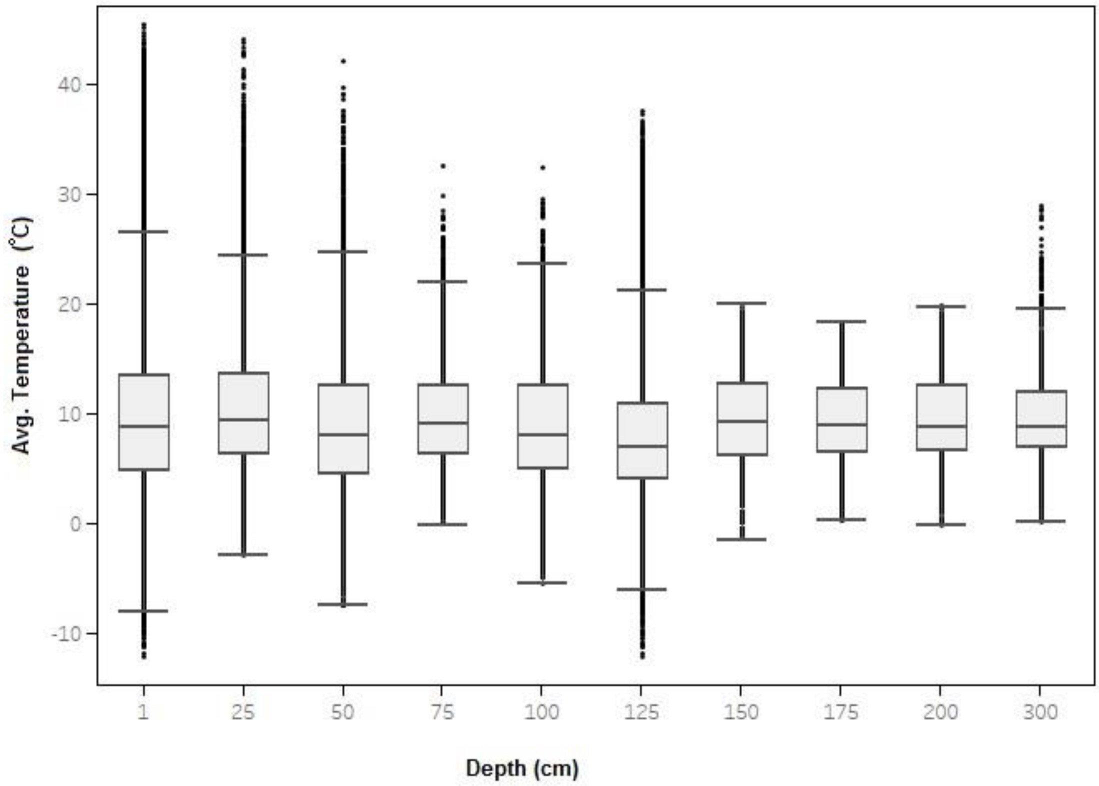
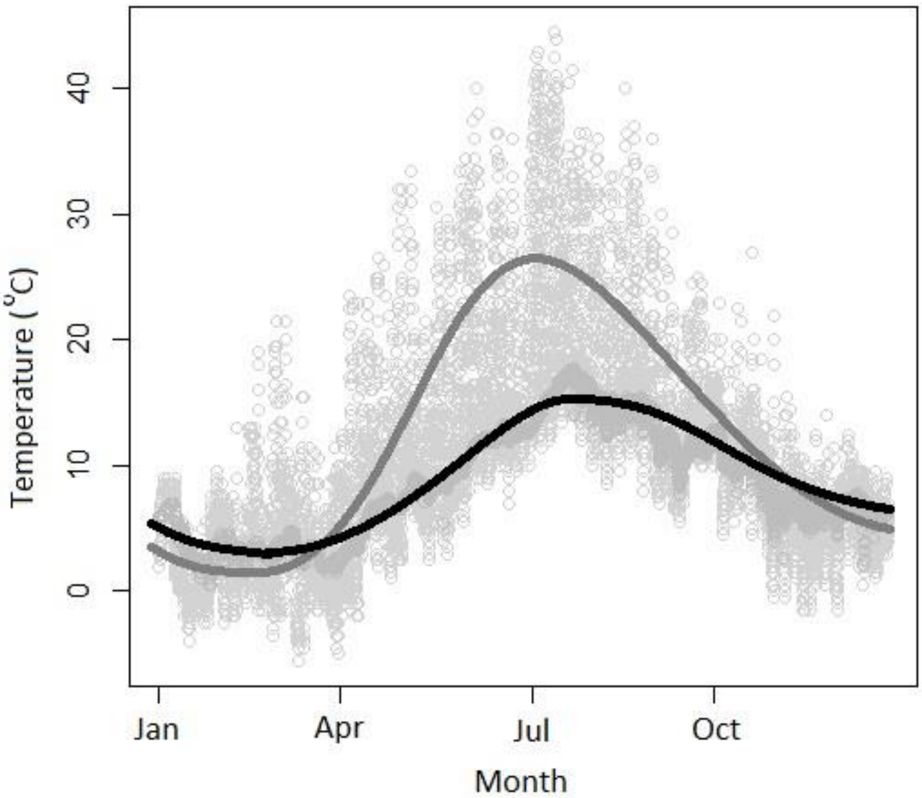


Figure 4.7 Boxplots showing the distribution of temperature taken from all depths in all grikes of this study.

4.3.2.2 Rate of change in temperature within the grike

Unlike relative humidity or light intensity, the temperature recorded at the surface and upper areas of the grike fluctuate above and below the more stable value (≈8-10°C) deeper in the grike. A number of studies of the grike microclimate have found that the temperature decreases with depth during the warm summer months and increases with depth during the cooler winter months (Figure 4.8) This led to a transition period in the autumn and spring during which equilibrium was reached between the external and internal temperatures (Burek & Legg, 1999; Alexander, Burek & Gibbs, 2007). While it is known that the grike temperature is stabilised both positively and negatively, as yet little study has addressed the rate of stabilisation and the direction in which stabilisation takes place, by looking at the rate of temperature change in the grike over a year.



● = surface temperature

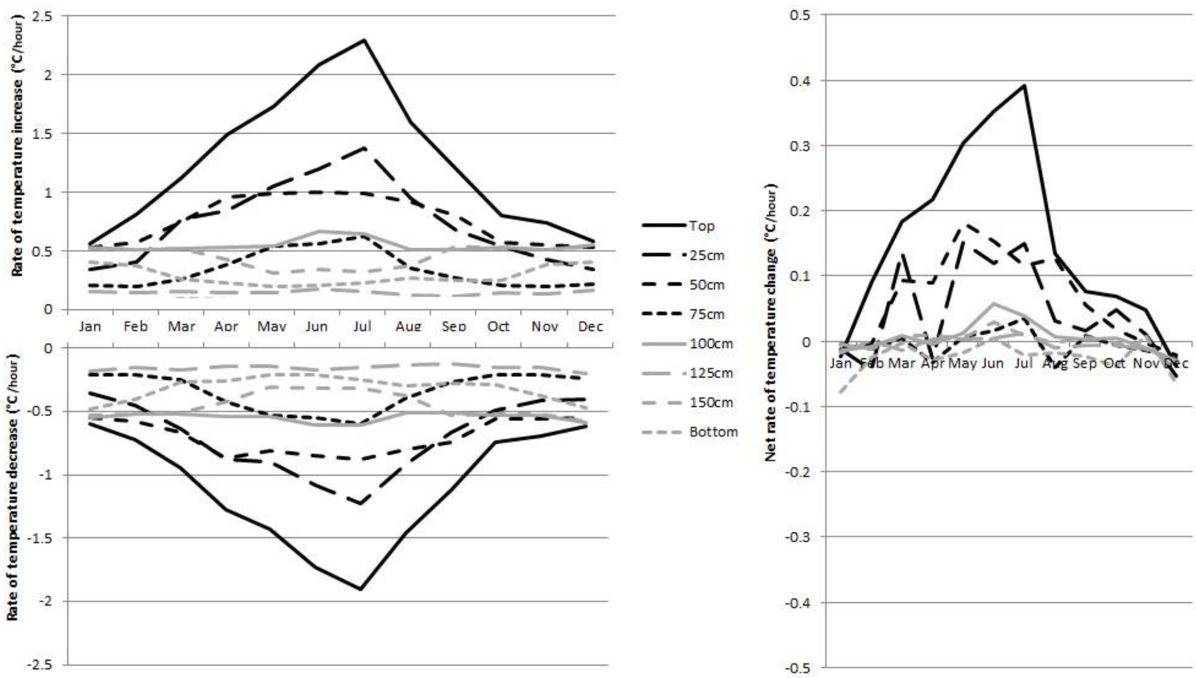
● = grike bottom temperature

Figure 4.8 Exemplification of temperature inversion taken from the NS Holme Park Quarry grike 2013 data set.

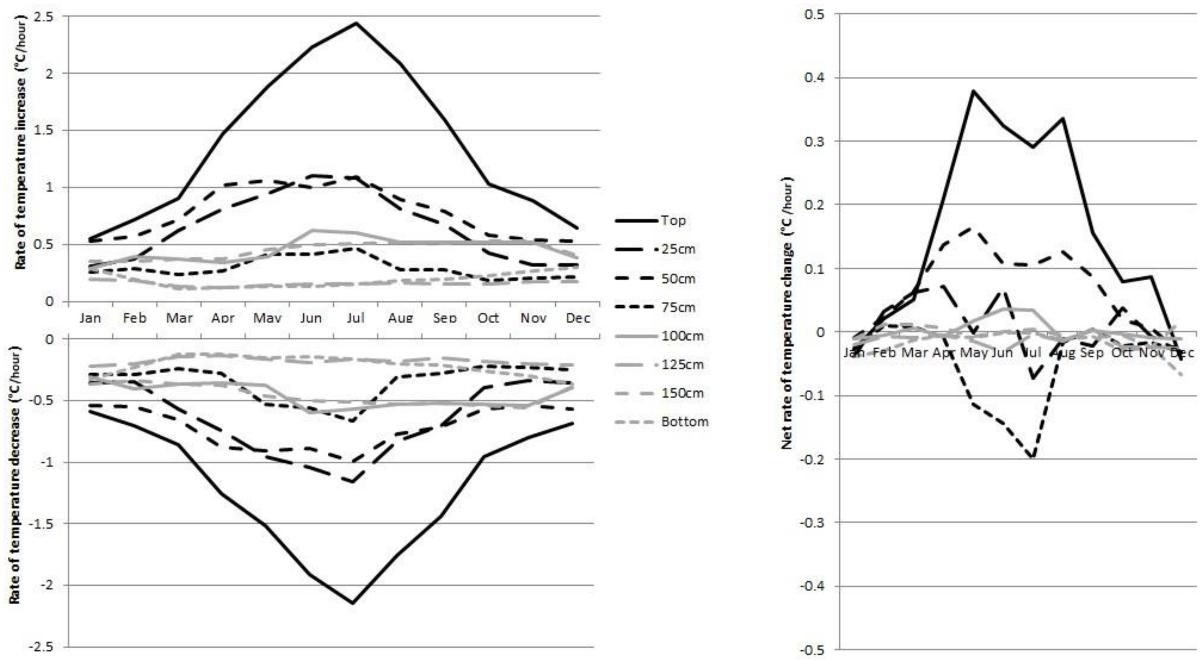
The rate of temperature increase and decrease was calculated for all the grikes on each of the limestone pavements in this study. The result of this calculation is exemplified in Figure 4.9.

4.3.2.2.1 Rate of change

On the left side of Figure 4.9, it can be seen that over a year, the rate of temperature change fluctuated. Both the rate of temperature increase and decrease became more rapid toward the summer and less rapid toward the winter. As the depth increased, there was also a decrease in both the positive and negative rate of change in temperature.



(a) Holme Park Quarry NS Grike



(b) Holme Park Quarry EW grike

Figure 4.9 Rate of change (left) and the net rate of change (right) in temperature in the Holme Park Quarry limestone pavement grikes.

4.3.2.2.2 The net rate of temperature change

On the right side of Figure 4.9, it was shown that there was a differing effect of the season depending on the region of the grike. There were two distinct regions:

The upper region appears in Figure 4.9 from the surface to 50cm.In the upper region of the grike, the net rate of temperature change throughout the entire year was almost entirely positive. This meant that in this zone, for most of the time, the temperature increased faster than it decreased. The NS grike and the EW grike have shown different peaks in the net rate of temperature change. In the NS grike, the net rate of temperature change peaked in July, whereas in the EW grike peaks appeared either side of July. The bifurcated peak in the EW plot was prominent in the Holme Park Quarry grike but less distinct on other sites. Most other sites have shown a lowered peak net rate of change in the EW grike when compared to the NS grike.

The lower region in Figure 4.9 can be found from 100cm to the base of the grike. Below 100 cm, the lower region has shown the rate of change in temperature to have been relatively equally positive and negative when compared to the upper region. As the depth increased, there was a greater proportion of time in which the net rate of temperature change was negative. Meaning that as depth increased the speed of temperature decrease was often more rapid than the speed of temperature increase. This was the case for both orientations of grike, and there was very little impact of orientation at this level.

Between the two regions at a depth of 75 cm in Figure 4.9, there appears to be somewhat of a transition zone which retains characteristics from both regions. In the Holme Park Quarry grike, at 75cm the profile of the rate of change in temperature was very different depending on the orientation of the grike. The net rate of change in temperature at 75cm in the NS grike was a combination of upper and lower regions. The same depth in the EW grike has shown a very strong negative net rate of change during the summer. This difference occurred only in the Holme Park Quarry and the Fanore pavements.

The results of this study further confirm the results found by previous work but also further indicate the sources of instability and stability in the grike. In the upper region of the grike, there was evidence of a strong influence of a heating force which was more powerful toward the summer. Subsection 4.3.3 of these results discusses the correlation between temperature and insolation that explains the positive net changes in temperature in the upper region of both grikes. As depth increased the heating force at the surface was increasingly counteracted and at times reversed by another cooling force, indicated by the increased speed at which temperature is reduced as depth increases. In Subsection 4.3.5, the high thermal mass of limestone clint relative to the air making up the grike was discussed. This high thermal mass of limestone indicates that the stone retains some heat energy over winter, which warms the lower reaches of the grike (Serway & Jewett, 2012). This system is indicated to function in reverse in summer. The limestone requires a lot of heat energy to increase its temperature by a small amount and therefore in summer is considerably cooler than the air. This relatively cold rock may reduce the rate of temperature increase deep in the grike and at times increase the rate of the decrease in temperature.

A similar effect has been used to cool or heat water by pumping it through pipes which descend many metres into the ground to where the temperature is considerably more stable than that outside (Henning, Motta & Mugnier, 2013). Early use of this technology has led to numerical simulations of the temperatures of soil and rock with depth, initially developed by Kasuda and Achenbach (1965).

4.3.2.3 There was a delay in temperature change with depth

In order to observe the delay to temperature change in the grike, a tool which is known as "dynamic time warping" was used. This is a process by which time-series data is adjusted chronologically back or forward in order to more closely match the data of a second data set (Berndt & Clifford, 1994). For all the grikes included in this study, the dynamic time warping process was carried out over a year using the R package "dwt" (Giorgino, 2015).

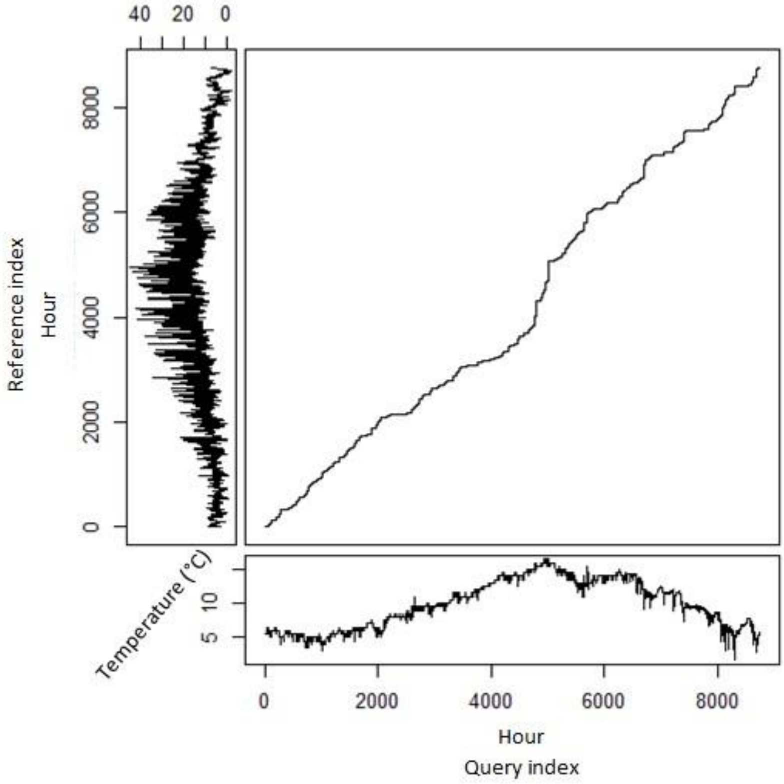


Figure 4.10 Three-way plot displaying the time-warping difference between the Reference Index (Surface) and Query Index (Bottom of grike 175 cm) in the Holme Park Quarry NS pavement over the year 2014.

Figure 4.10 shows that the two data sets are in agreement for the majority of the time, indicated by the 45° angle of the line in the plot equidistant between the two axes. Toward the summer, the line on the plot deviates from 45° toward the query index. This is interpreted as grike bottom temperature becoming increasingly negatively out of step with the surface temperature, indicating that there was a delay in the change in temperature. In the autumn this deviation is reversed, and the line resumes the 45° trajectory, indicating that agreement between the data sets has returned.

2.3.4 Periodicity of the grike temperature

The most striking characteristic of any time series temperature plot is the periodic nature of the temperature change. Cyclical periods within the data have been of varying length matching several different natural cycles.

4.3.2.4 Periodicity by month and by hour

By splitting the data by month, it has been possible to characterise the changing relationship between the grike and surface microclimates over a year. Likewise, by subdividing the temperature data by hour, the median daily cycle can be observed.

Figure 4.11 shows that over the year, there was a periodicity in temperature, at both the surface and within all depths of the grike. The periodicity is manifest as a sinusoidal pattern of high and low median temperature and temperature variation over the year, reaching a maximum in summer and minimum in winter. The fluctuations in temperature decreased with depth so that in spring and autumn there was a temperature inversion. The inversion means that the surface was warm compared to the grike in summer, but parts of the grike were warmer than the surface in winter.

Figure 4.12 shows that a similar trend which occurred over a year also occurred over a day. There is a cyclical rise and fall in median temperature and variance which reaches a maximum toward midday and a minimum during the night. When comparing the seasonal temperature cycle to the daily cycle, the deviation from the median is lowest over a day. The lack of deviation is such that at levels deeper than 150cm, there is almost no change in the median, upper or lower temperature quartiles over a day.

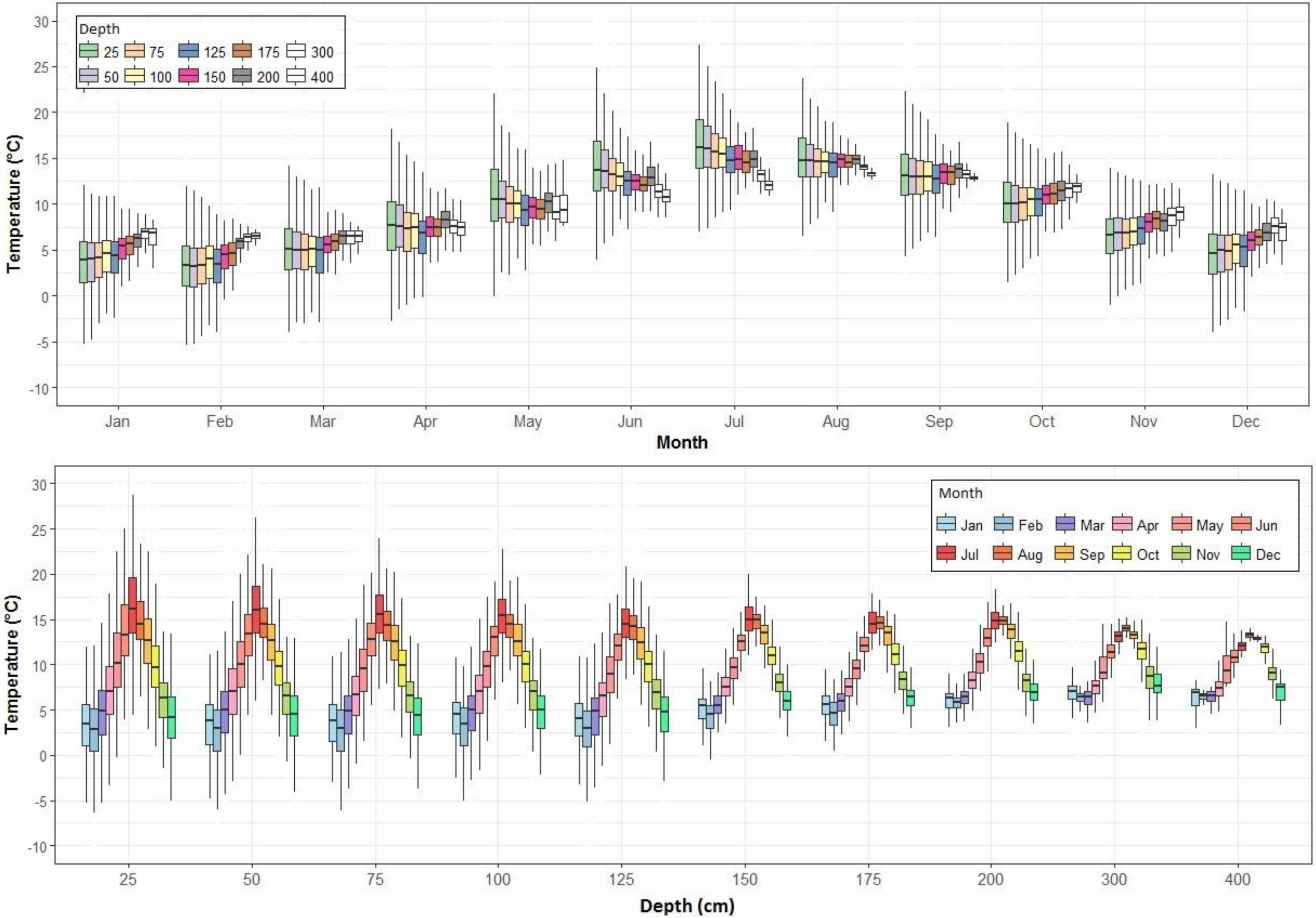


Figure 4.11 Boxplots illustrating the cycle of temperature over a year in the grikes of the limestone pavements studied.

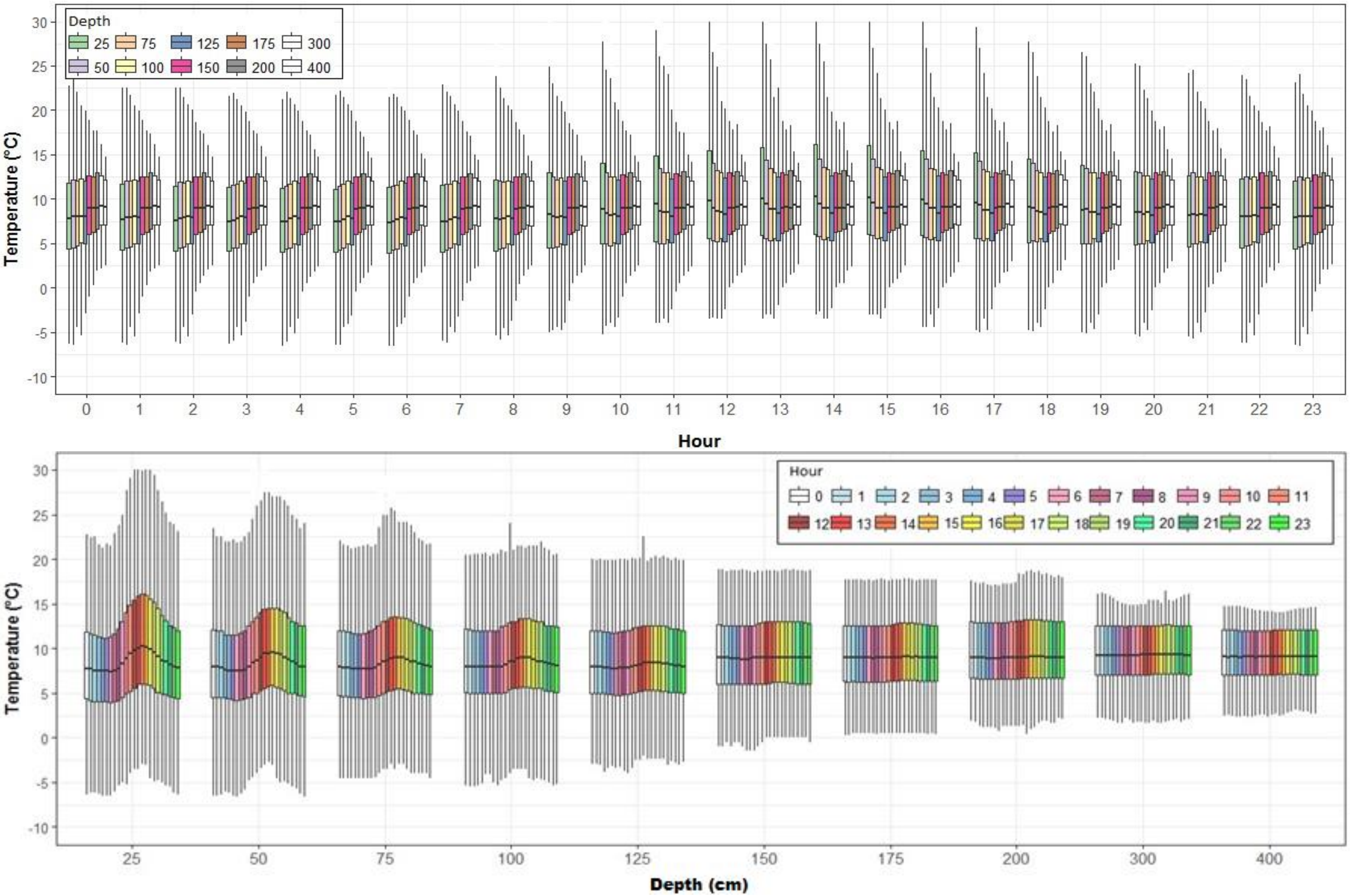


Figure 4.12 Boxplots illustrating the cycle of temperature over a day in the grikes of the limestone pavements studied.

4.3.2.5 Combined periodicity by the hour and season

The periodic fluctuations in temperature observed thus far can combine and produce cumulative interactions (Brown, 2004). The data for each season was subdivided by the hour in order to test the hypothesis that there is an interaction between the yearly temperature fluctuation and the daily temperature fluctuation. Seasons from this point are used to describe combined data from sets of three months, where summer includes June, July and August, and winter includes December, January and February.

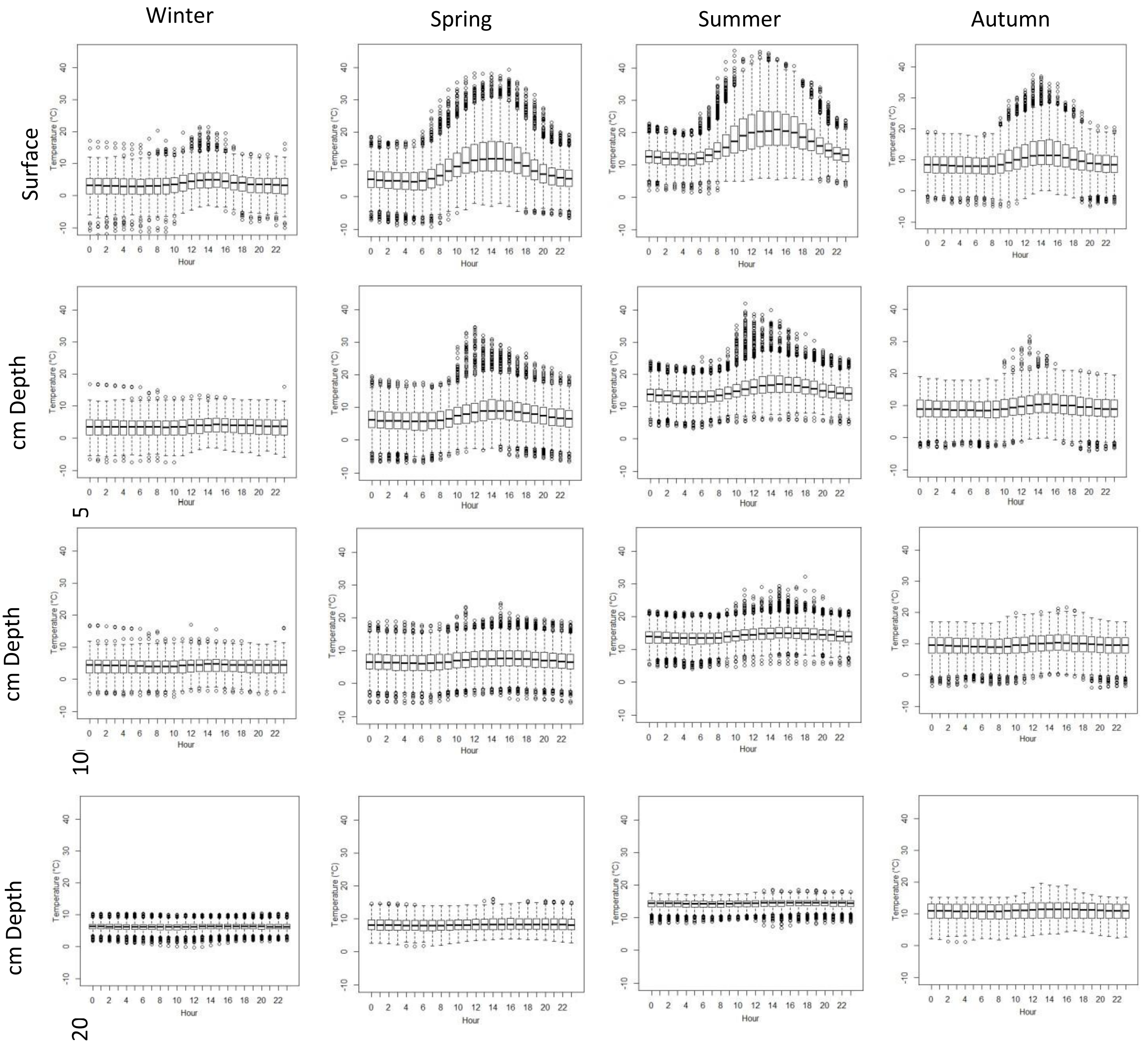


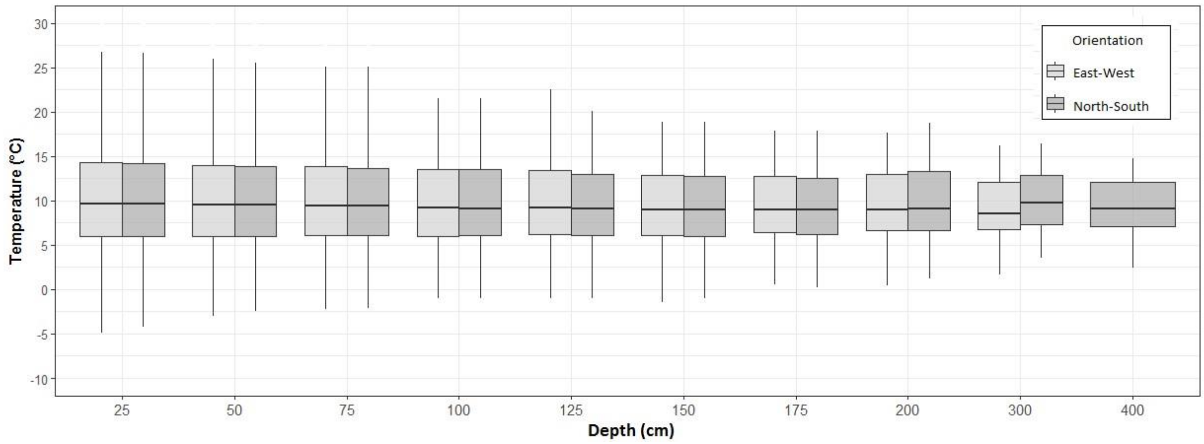
Figure 4.13 Boxplots demonstrating the effect of the season, on hourly temperature data taken from all grikes in this study.

It is observed in Figure 4.13 that the character of the daily temperature period was different depending upon the time of year, and the interaction between the two periods was cumulative. The grike temperature appears to have been increased by both season and time of day at all levels of the grike such that seasonal proximity to summer and spatial proximity to the surface both amplify the diurnal temperature amplitude.

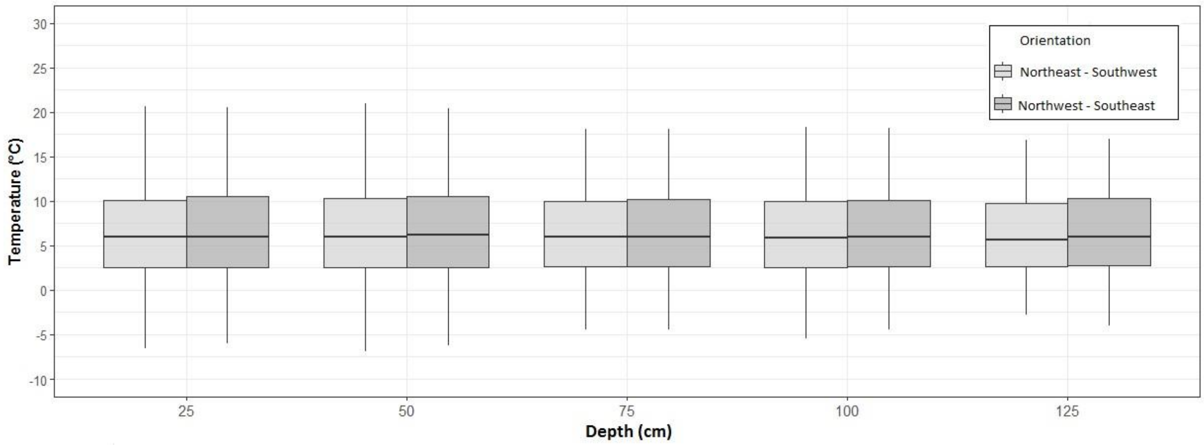
4.3.2.6 Temperature and Orientation

4.3.2.6.1 Orientation and depth

The relationship between temperature and depth over a year are compared between North to South (NS), East to West (EW), Northwest to Southeast (NW) and Northeast to Southwest (NE) grikes in Figure 4.14.



(a) NS and EW orientated grike



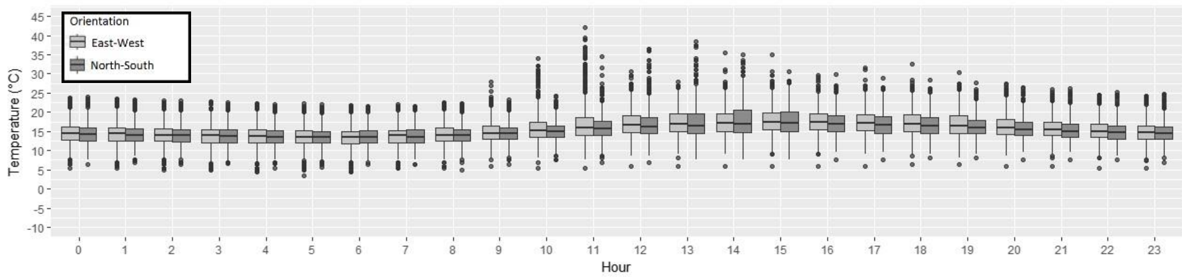
(b) NE and NW orientated grike

Figure 4.14 Boxplots showing the effect of grike orientation on the temperature at different depths for all grike data.

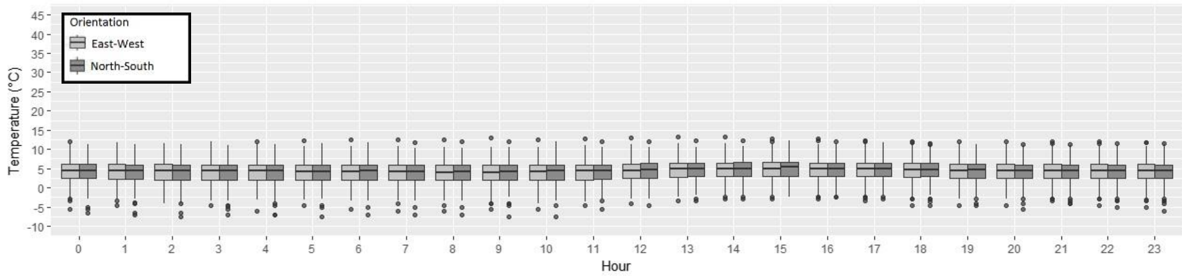
These show that there was only a slight difference in the median and range in temperature between principally orientated grikes, with the EW grike becoming warmer than the NS grike with depth until 200cm where the NS grike is warmer. There is also little observable difference in the values of temperature between NW and NE grikes.

4.3.2.6.2 Orientation, depth, season and hour

The data was split to show just season and temperatures. Splitting the data was done in order to contrast the different times of the year, which have been shown to impact temperature in the previous Subsection. Figure 4.15, Figure 4.16 and Figure 4.17 contrast the temperatures in the EW grike (light grey) with those in the NS grike (dark grey) over a day.



a) Summer



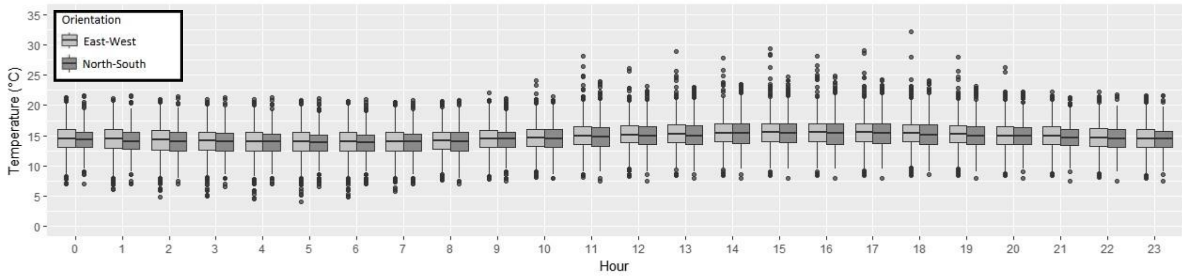
b) Winter

Figure 4.15 Boxplot showing temperature over a day at 50cm depth, in grikes orientated on the cardinal compass directions.

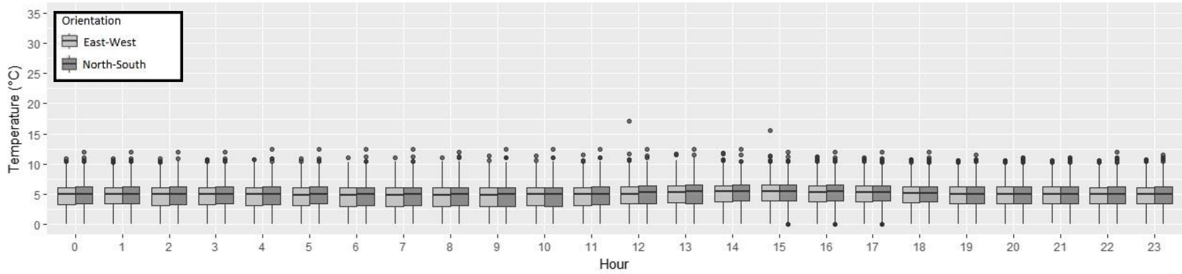
In Figure 4.15, there are slight differences in the temperature in the EW and NS grikes at 50 cm depth. During summer the temperature was greatest in the EW grike throughout the day apart from at 14:00 and 15:00. These periods were a short amount of time after when the sun was at its apex in the sky. During winter there was very little difference in temperature between the orientations.

In Figure 4.16, the temperature at 100cm in each orientation of grike was shown to be similar. However, the EW grike was a small amount warmer throughout the day. The NS grike temperature reached closest to that of the EW grike at 14:00 once more. During winter there was still very little difference in temperature between the orientations.

Figure 4.17 shows that the median temperature at 200cm in both NS and EW grikes were very similar throughout the day; however, in summer, the EW lower quartile dropped lower than that of the NS grike. The winter temperature was slightly higher in the EW grike than in the NS grike.

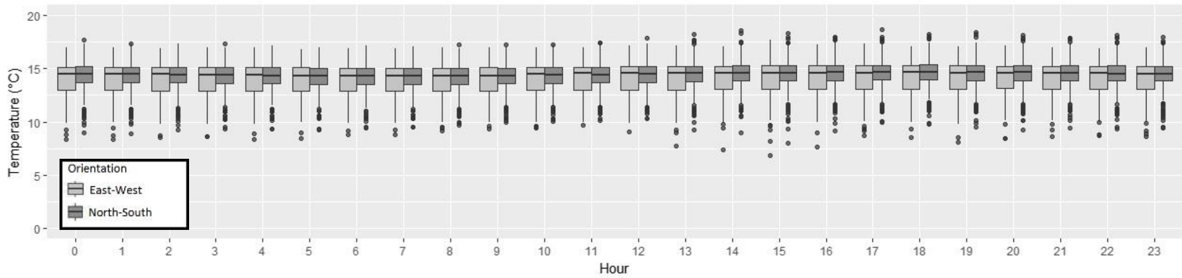


a) Summer

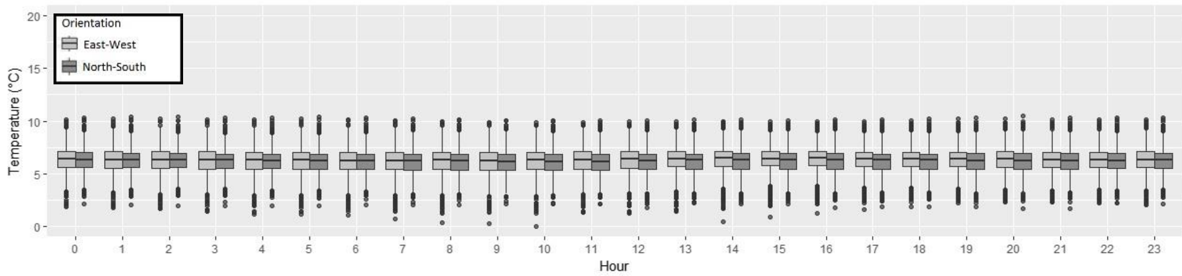


b) Winter

Figure 4.16 Boxplot showing temperature over a day at 100cm depth, in grikes orientated along the cardinal compass directions.



a) Summer



b) Winter

Figure 4.17 Boxplot showing temperature over a day at 200cm depth, in grikes orientated along the cardinal compass directions.

The periods over which the NS grike was warmer than the EW grike coincides with the period over which the sun was at its apex. The comparative light intensity in the grikes has been investigated to explore this correlation further in the next subsection

4.3.2.7 Subsection conclusion

Previous studies of grikes provided a foundation from which to make assumptions about the behaviour of the grike microclimate, however with a greater quantity of data collected over a longer period it has been possible to observe several different aspects of the grike microclimate which until now remained unknown, to the knowledge of the author.

The long term study of grike temperature has allowed for the observation of grike temperature fluctuations over the course of a day and over a year. There has also been observed to be a variation in grike temperature between different orientations of grike. The time of day and year appear to interact with one another and with orientation, and all variables have been observed to interact with depth to create a picture of the temperature within the grike. These interactions can be used to simulate the grike temperature and could also be used to project the future of grike temperature under conditions of anthropogenic climate change.

In this subsection, it has been observed that the surface temperature changed rapidly, whereas the change in the temperature at depth was reduced and often delayed. The observed reduction and delay in temperature change were highly influenced by the time of year, but the time of day influenced only to reduce temperature fluctuations at the bottom of the grike. These findings indicate that this reduction in temperature variance is not a rigid phenomenon. Instead, the stability of the grike is flexible, and higher surface change in temperature results in a greater change in temperature deep in the grike.

In a rigid system, the temperature is unimpeded at the surface and limited by increasingly rigid limits as the grike increases in depth. This is not the case in Subsection 4.3.2. Here the 2014 mean temperature in the bottom of the grike was not restricted, and changed in line with the surface temperature.

A flexible system is shown in Figure 4.9, where the grike temperature is increasingly forced toward a mean as depth increases. This flexible system is further shown in Figure 4.10, which illustrates a temperature which is increasingly slow to change as depth was increased. The temperature was, however, at no point limited and could be changed if a consistent directional change were applied from the surface as occurred in 2014.

One possible reason for the flexible stability of the grike temperature is the surrounding limestone of the clint and high thermal mass of the limestone. This high thermal mass retains a more constant temperature throughout the year, which then influences the temperature of the deep grike. The high thermal mass of the limestone requires a lot of heat energy to change its temperature and releases energy to the environment very slowly. These combined features give the limestone high thermal inertia. Bodies with high thermal inertia take a long time for the temperature change to register (Šesták, Hubík & Mareš, 2017), as was observed in the difference between temperature change at the surface and grike bottom (Figure 4.10). The delay in temperature change within the grike indicates further that the microclimate at the grike bottom is dominated by the surrounding rock and less by the outside environment. Thermal inertia has been observed in caves where the mountain in which they are situated provides a thermal mass which stabilises temperatures to a very great extent. This delay in temperature change does not mean that temperature does not change. The effects of global warming have been modelled within caves and hypothesised to have a delayed impact despite the separation from the global climate (Badino, 2004).

The findings of this section have several implications for further study of limestone pavements. This subsection shows the first instance of the grike exhibiting a zoned microclimate. This theme recurs throughout this study and may be important in the identification of grikes that may provide microrefugia. By showing the periodic nature of temperature's relation to the external climate and grike form, it has been possible to propose the methodological basis for simulating temperature in the grike using linear regression. By identifying the primary periods over which changes in temperature take place, steps have been taken to identify key variables which can be used in grike microclimate simulations. The delay in temperature change observed with depth into the grike could also influence the simulations used to provide informative scenarios of the grike temperature. The delay observed in this study is not a constant and could prove difficult to recreate with any accuracy, so further discussion of this topic is detailed later in this study in Chapter Six.

4.3.3 Radiative heating in the grike

The cyclical heating which has been observed in the previous subsection underpins the impact that radiative heating has upon the grike. This subsection explores this connection further in order to prepare to simulate the grike temperature.

4.3.3.1 Zonation in light intensity

The speed of temperature change within the grike has been observed to occur at different rates depending on specific depths within the grike. Figure 4.18 shows similar zonation in the amounts of light impacting on different depths of the grike.

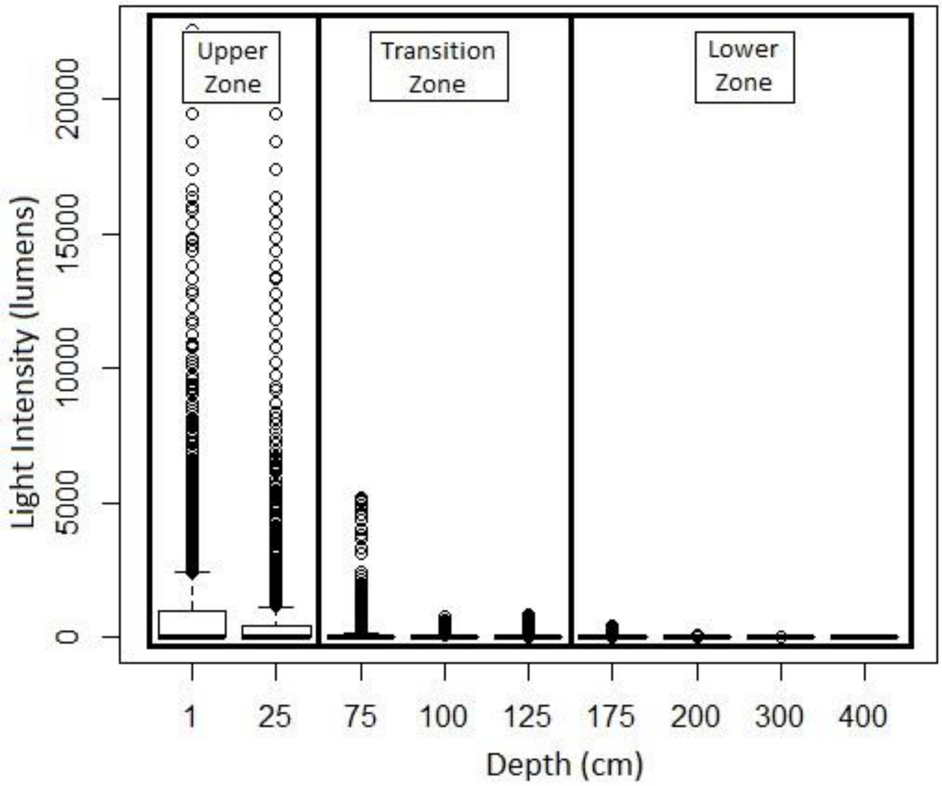


Figure 4.18 Light zonation within the grike, demonstrated on a boxplot showing the light intensity recorded from all grikes at all depths used in this study.

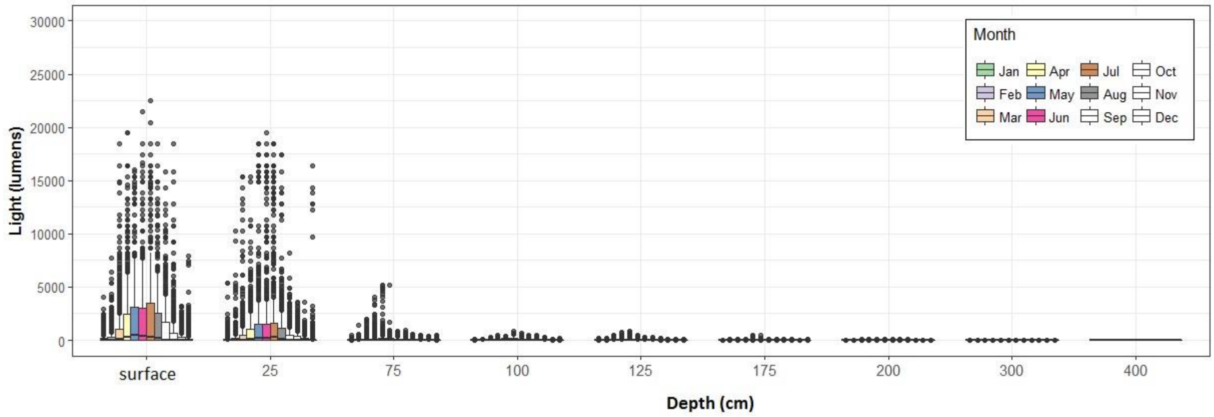
Upper Zone: Between the surface and 25 cm – In this area of the grike, the median light intensity was furthest from zero, and the upper quartile and 95th percentile were visibly higher than zero. Light impacted this area of the grike frequently and with high intensity.

Transition Zone: Between 75cm and 125cm – In this grike area, the median, upper quartile and 95th percentile were all almost indistinguishable, there were still several outliers recorded in this region. This indicates that light infrequently impacted this area of the grike, and the intensity was low.

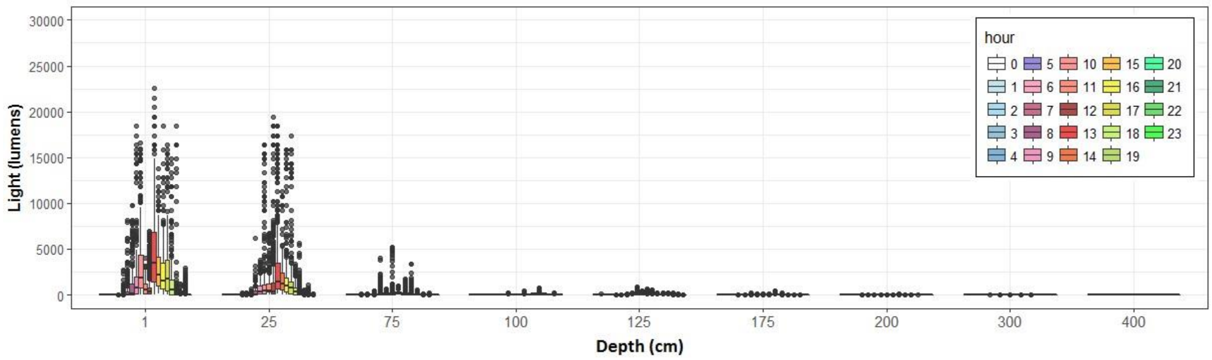
Lower Zone: From 175cm down - In this area of the grike, light intensity reported by the boxplot was frequently indistinguishable from 0, and there were very few outliers, This shows that only small amounts of infrequent light impacted this region and for the majority of the time light levels were close to zero.

4.3.3.1.1 Periodicity of light intensity

The light intensity at the surface and at 25cm reflect the seasonal cycle of light intensity which was experienced locally. At a depth of 125cm and 200cm, there was very little light at any time of year (Figure. 4.19).



a) Light intensity over a year



b) Light intensity over a day

Figure 4.19 boxplot of light intensity recorded in all grikes over one year (a) and over one day (b).

The light intensity over a day (Figure 4.19 b) reflects the intensity observed over a year. The surface and 25cm depth resemble the expected fluctuations in temperature over a normal day, whereas 125cm and 200cm show a median of close to zero for the entire day.

To investigate whether the annual and diurnal periods interact, the data were subdivided further by both the seasons and by the hour so that it was possible to view the relationship between depth and light intensity by the hour for different times of the year.

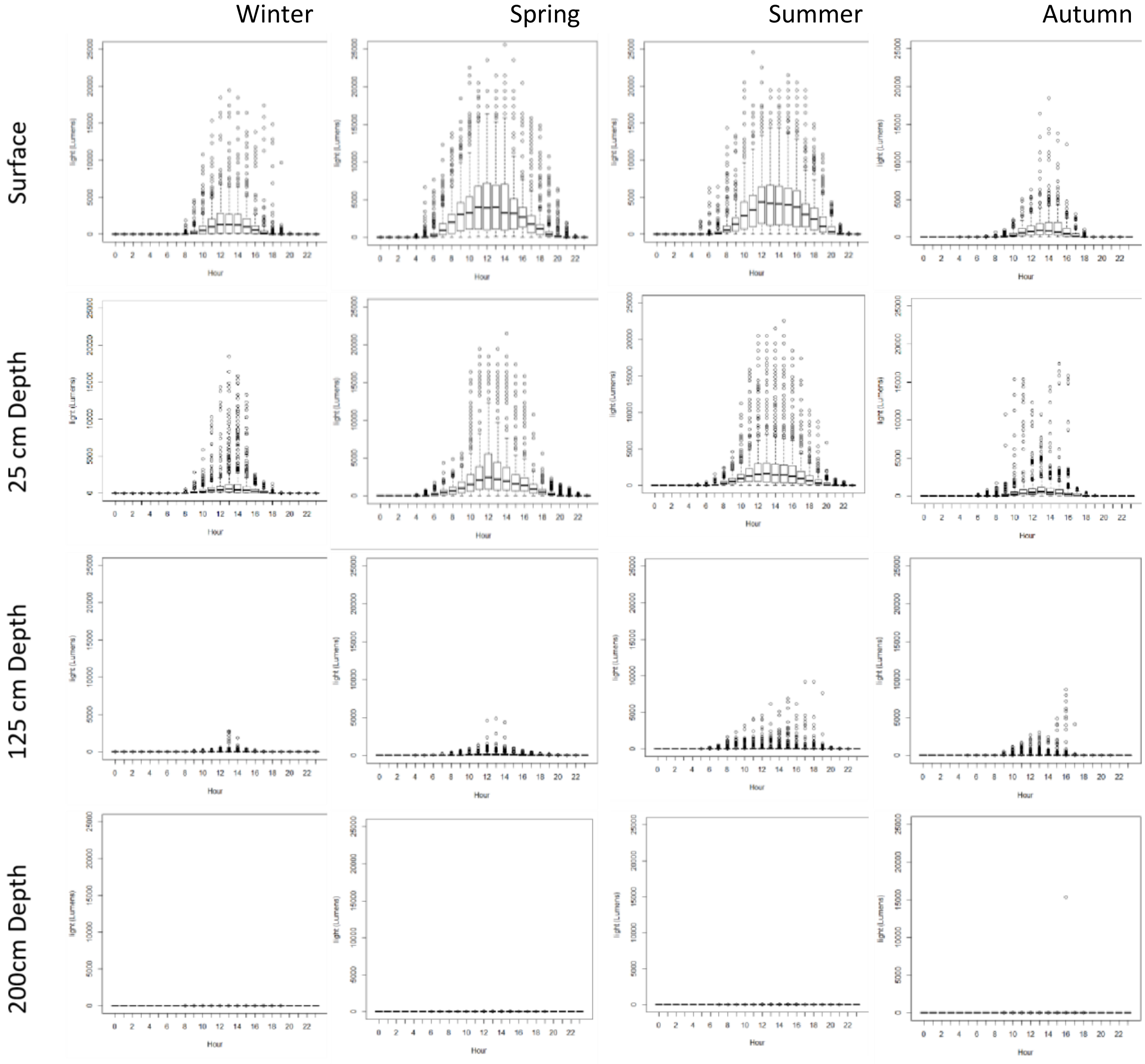


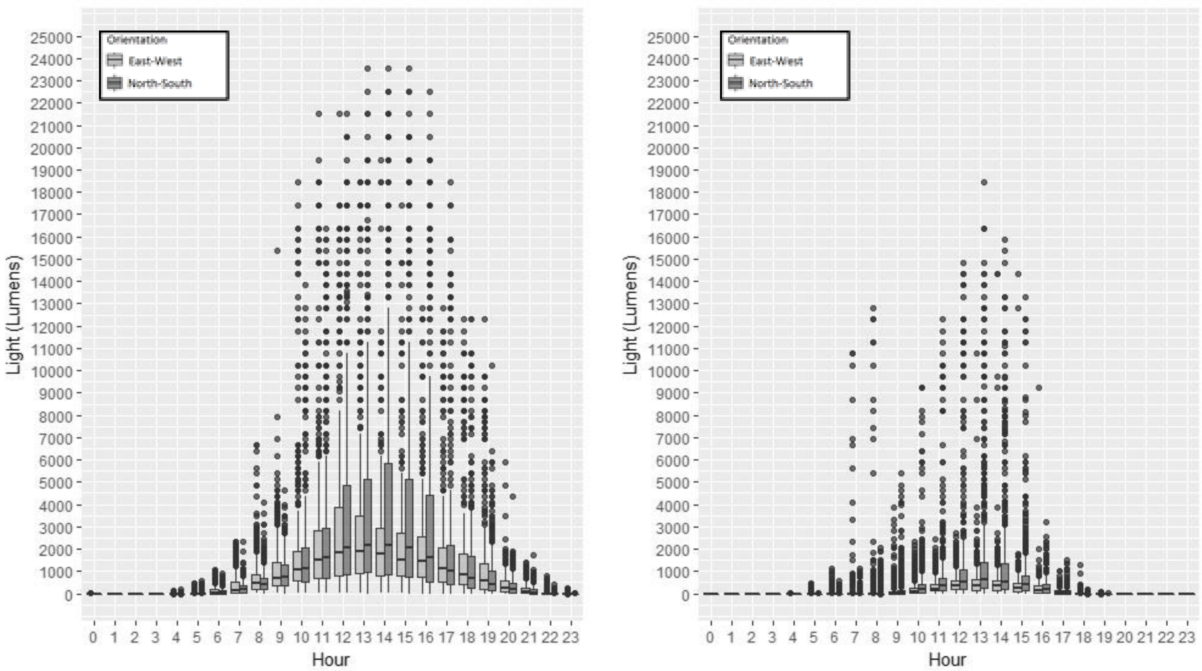
Figure 4.20 Boxplots demonstrating the effect of season, on hourly light intensity data taken from all grikes in this study.

Figure 4.20 shows that the diurnal and seasonal patterns in light intensity did interact to either add or diminish the light intensity observed over a day. Figure 4.20 also shows that there was a finite window of high light intensity which lasted for longest at the surface, during summer, and was diminished by both depth and change in seasonal day length.

The zoning discussed in Subsection 4.3.2 and described at the beginning of this subsection seems to be somewhat reflected during the light intensity cycles. The surface and 25cm depth have been shown to reflect changes in the ambient light intensity with only minor restriction. Light recorded at 125cm in the second grike zone had shown highly restricted light intensity and outliers of high intensity only when the sun was highest. Finally, the light recorded at 200cm in the third zone has shown almost no light all year round. These zones closely reflect the zones discussed in Subsection 4.3.2, which relate to the rate of temperature change in different areas of the grike. In Subsection 4.3.2.2, the upper region of the grike from the surface to 50cm was rapidly changeable, and the lower region from 100cm to the base changed relatively slowly. This suggests that there is an interaction between light intensity and temperature. The light intensity recorded in the grike is compared between the two orientations, to explore the spatial component of the relationship between temperature and light intensity.

4.3.3.1.2 Light and Orientation

The amount of light impacting grikes of differing orientation has been hypothesised to be highly subject to depth, time of year and time of day (Burek & Legg, 1999). In order to isolate the differences between the two orientations and make direct comparisons to temperature, the light intensity within the grikes was displayed per hour of the day during summer and winter.

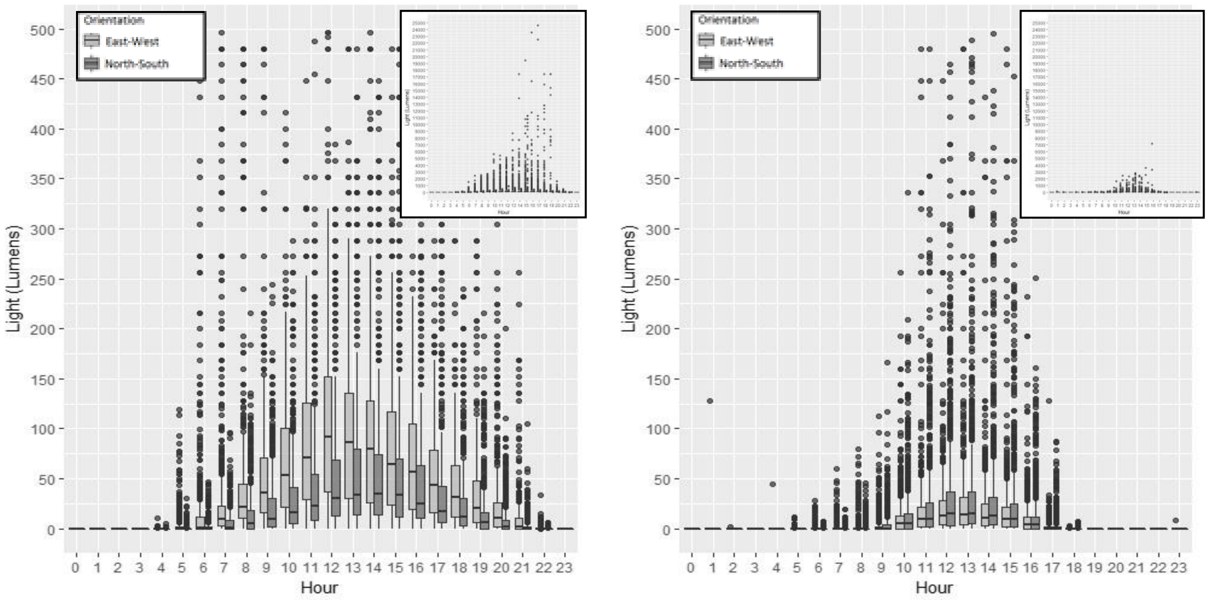


a) Summer b) Winter

Figure 4.21 A comparison of light intensity recorded at 25cm in all NS and EW grikes used in this study.

Each of Figure 4.21, Figure 4.22 and Figure 4.23 reiterate the finding of Figure 4.20, showing that grikes received decreased light at greater depth and during winter. These plots all show that light entered the EW grike earlier than the NS grike; however, the light intensity in the NS grikes increased more rapidly, forming a pyramidal distribution. This distribution may be symptomatic of the shorter period over which the NS grike received light. When different depths and seasons were compared, it was apparent that the hour of peak light intensity in the EW grike was later as light levels decreased, whereas the NS grikes had a stable time of peak intensity.

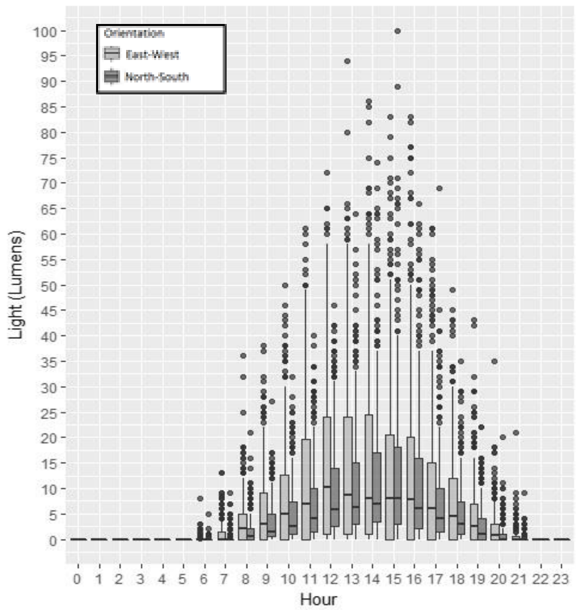
Figure 4.21 shows that light intensity recorded in the 25cm grikes was greatest in the EW grike during the start and end of the day, but switches such that the NS grike received most light toward midday.



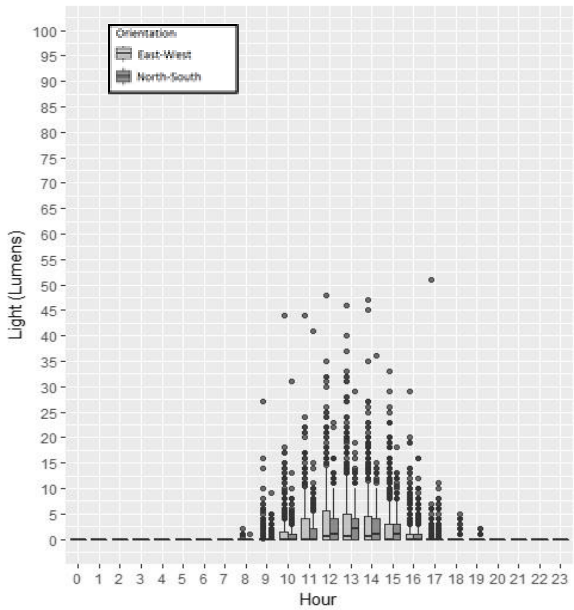
a) Summer b) Winter

Figure 4.22 A comparison of light intensity recorded at 125cm in all NS and EW grikes used in this study.

Figure 4.22 shows that at 125cm, the intensity of light in the two primary orientations of grike was highly influenced by season. During summer the EW grike recorded highest light intensity throughout the day whereas in winter the NS grike attained highest light intensity toward midday, as at 25cm.



c) Summer



d) Winter

Figure 4.23 A comparison of light intensity recorded at 200cm in all NS and EW grikes used in this study.

At a depth of 200cm, Figure 4.23 shows that the EW grike had the highest light intensity throughout the day, except four hours surrounding midday over winter. During this time the EW grike had a higher upper quartile, but the median light intensity in the NS grike was higher.

4.3.3.1.3 Correlation between Temperature and Light

Through sequential testing of the data, it was found that both temperature and light intensity have a similar relationship with depth and orientation. Both temperature and light intensity have shown a seasonal and diurnal cycle which interact with one another. Commonalities between temperature and light intensity are now quantified through correlation to investigate the relationships and interactions in the grike microclimate further.

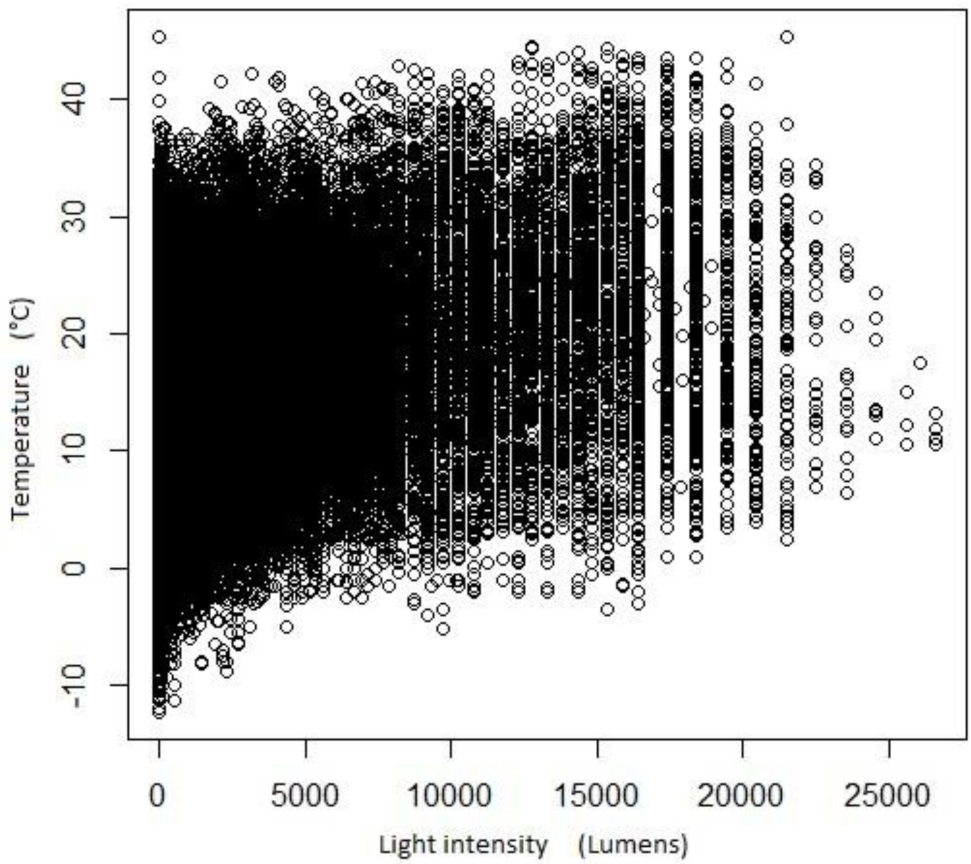


Figure 4.24 Scatter plot of temperature and light intensity in all grikes studied.

Figure 4.24 shows a plot of temperature against light intensity for all data. There appears to be a slight upward trend, indicating that there is a possible positive correlation between light and temperature. The Spearman's rank coefficient was calculated over different periods and different orientations in order to investigate the relationship of temperature and light over time. A non-parametric test was used due to the single-tailed distribution of light intensity data.

Figure 4.25 shows the Spearman's rank coefficients for all the data collected in the NS and EW grikes, respectively. This data was further subdivided by month and by depth to illustrate how the correlation alters over the year. All points shown in Figure 4.25 have a $p < 0.05$.

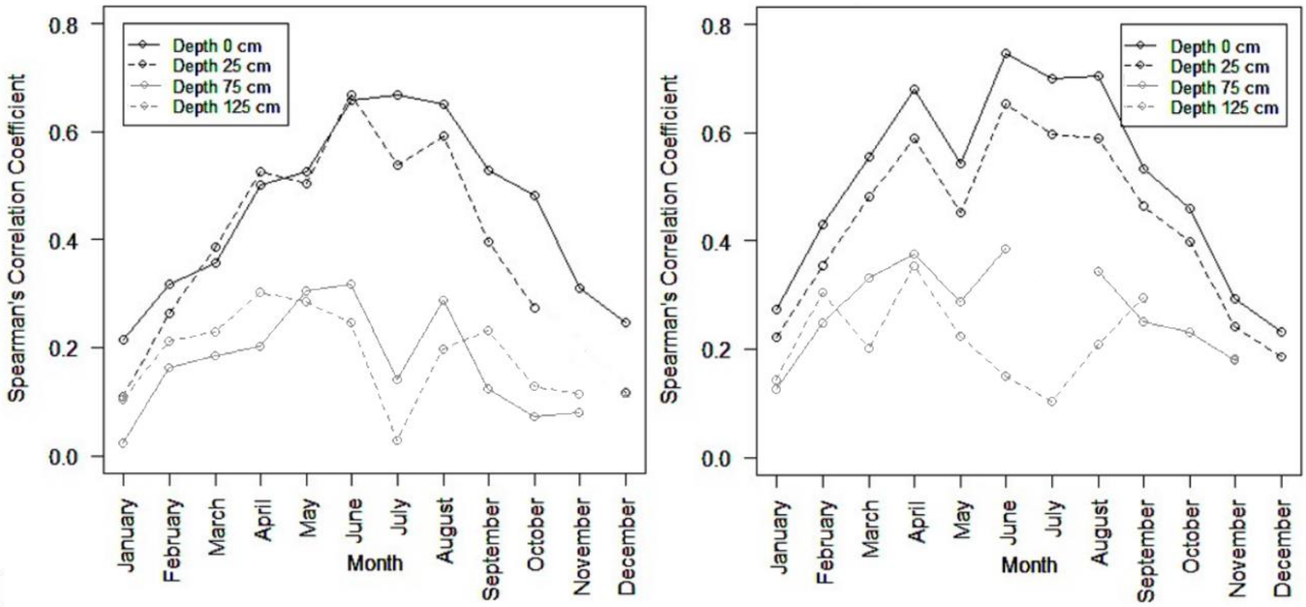


Figure 4.25 Spearman's correlation coefficient between temperature and light intensity for all EW (left) and NS (right) grikes over a year. Points for which the value of p was below 0.05 are not shown.

At the surface and 25cm into the grike, there was a gradual increase in the strength of the correlation as the year progresses into summer; this then decreased similarly over the latter half of the year. There was very little difference between the NS and EW grikes at these levels, apart from a decrease in the magnitude of the correlation in the NS grike during May and not observed in the EW grike. At depths 75cm and 125 cm, both orientations have shown an increase in correlation between light and temperature from January to April and a decrease between September and December. Both the increase and decrease in correlation were more gradual than at the surface or at 25 cm.

Between May and August, there was a difference between the two orientations. At a depth of 75cm in the NS grike, the strength of correlation stayed fairly stable, whereas, in the EW grike, the strength of correlation decreased until July when it increased once more. At a depth of 125cm, both orientations of grike have shown the same dip in Spearman's rank correlation coefficient over the summer. This reduction in correlation was a result of decreased light intensity with depth and a more stable mean temperature during the summer. In Grikes of depth 75cm or below, the orientation of north to south and winter months all appeared to lead to fewer significant values of Spearman's correlation coefficient.

Similar to Figure 4.25, Figure 4.26 shows the Spearman's rank coefficients for all the data collected grikes of two orientation, but subdivided by hour and by depth to illustrate how the correlation alters over a day. All points shown in Figure 4.26 have a $p < 0.05$.

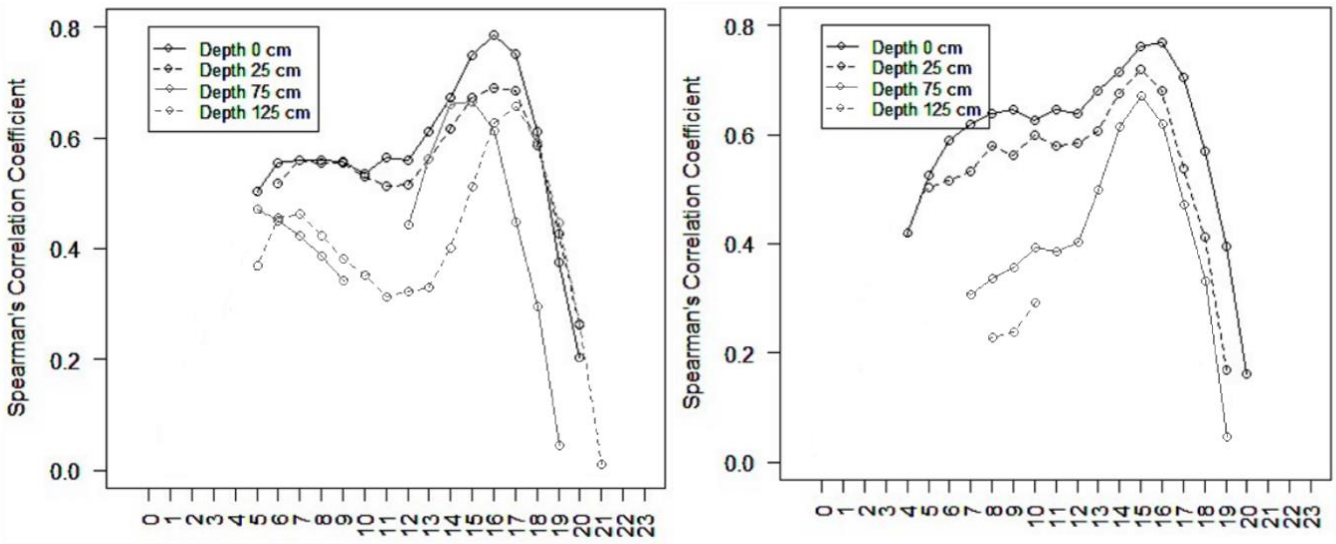


Figure 4.26 Spearman's correlation coefficient between temperature and light intensity for all EW (left) and NS (right) grikes over a day. Points for which the value of p was below 0.05 are not shown.

At all depths and in both orientations of grike, there were two peaks in the correlation between temperature and light intensity occurring in the morning and evening. There was a reduction in correlation between the peaks that became more pronounced as depth increased, irrespective of grike orientation.

In the NS grike, the first peak was less pronounced than in the EW grike, and the NS grike also experienced a reduction in all peak correlations as depth increased. The EW grike had two well-defined peaks which were maintained at all depths.

Grikes of depth 125cm, the orientation of north to south and the hours between 8:00 and 22:00 all appear to have led to fewer significant values of Spearman's correlation coefficient. The NS grike also had very few points for which the Spearman's correlation coefficient was significant.

4.3.3.2 Discussion of the links between Temperature, Light and the orientation of grikes

Microclimate research conducted by Geiger, Aron and Todhunter (2009) did not cover grikes specifically but did examine the microclimates of ploughed furrows, hollows and human-made trenches. In this research discussed in Subsection 2.2.4, variable microclimates were found in different orientations and on different vertical faces. The difference in temperature was attributed to the aspect and angle of the slope receiving much stronger solar radiation. Trench-like hollows with steep or near-vertical walls have been previously discussed as being a close analogy to a grike (Yarranton & Beasleigh, 1968). Such trenches were discovered to be comparatively warmer than the surrounding environment at night. If the analogy of trenches to grikes is accepted, it could be expected to find grikes displaying the same or similar characteristics to this trench discussed by Geiger, Aron and Todhunter (2009). The position of Great Britain and Ireland in the northern hemisphere means that the sun does not pass from east to west directly overhead but is biased toward the south by between 28° to 75° (zenith angle) depending on location and season. This bias means that the amount of insolation received into the grike is determined by its depth, aspect, and angle of dip and orientation. Geiger, Aron and Todhunter (2009) stress the influence that orientation and aspect have on the light entering a depression over different ties of day and year. In order to test these assumptions, a simulation was created in Appendix one to map the extent of light within a grike using the angle of light entering a 20cm wide grike of differing orientation. In addition to the angle of the light, there are three further factors which contribute to the strength of light reaching into a grike.

Albedo – The albedo of the rock dictates how the rock absorbs much of the energy from the light and how much is reflected to continue into the grike. Grey cement, similar to limestone reflects between 13% and 33% of light (Prado & Ferreira, 2005). This level of absorption indicates that the energy in the light beam is soon reduced if a beam is not direct.

Atmospheric attenuation – at dawn and dusk the light reaching the Earth passes through considerably more of the gases and particles in the atmosphere surrounding the Earth before it reaches the ground than it does at midday. The atmosphere absorbs a portion of the sun's energy reducing the fraction reaching Earth (Khavrus & Shelevytsky, 2010).

The angle of incidence – at dawn and dusk, the sun's light is spread over a larger area than at midday. By increasing the area of the ground over which a beam of light is spread the amount of energy available to any point within that area is proportionally reduced (Khavrus & Shelevytsky, 2010)

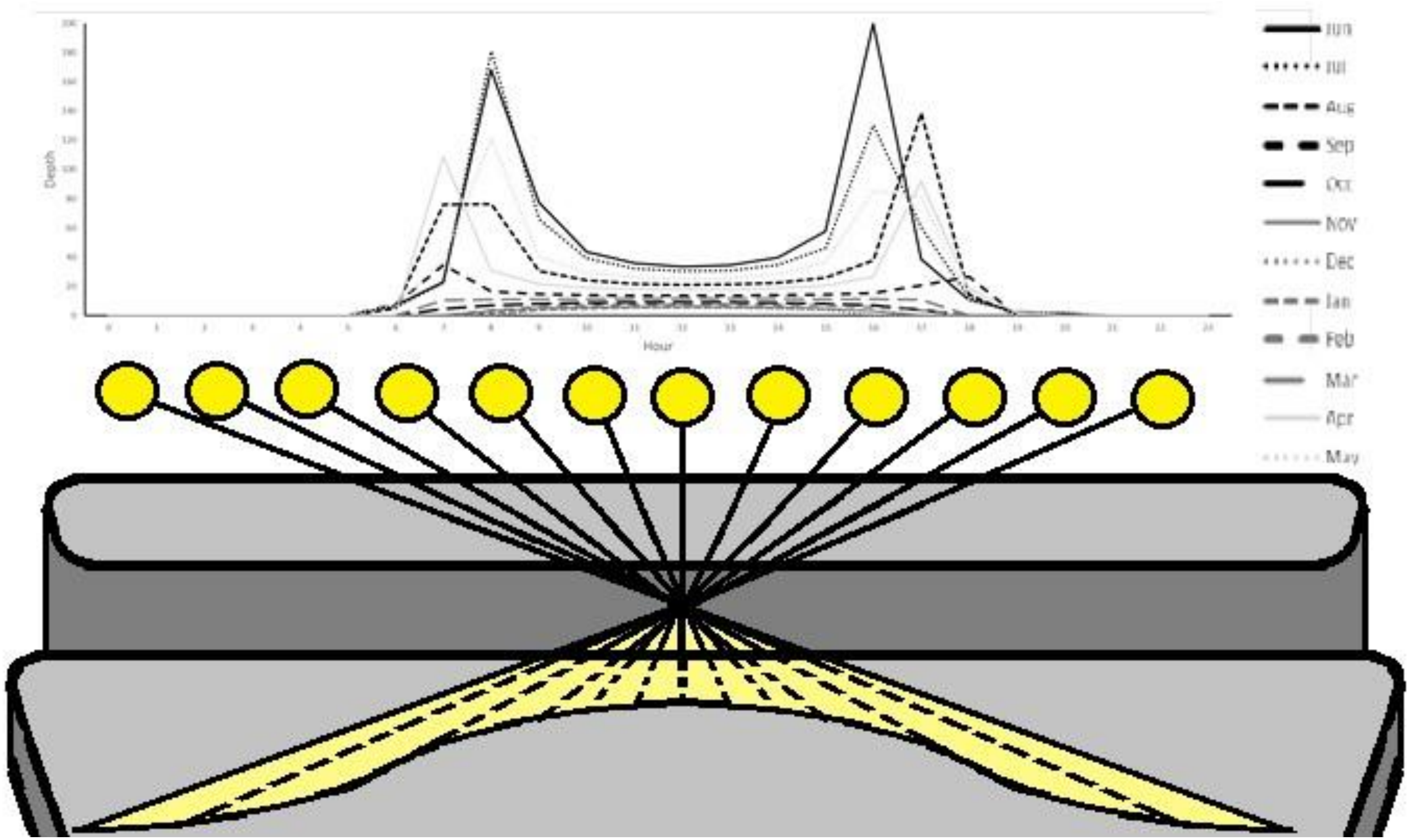


Figure 4.27 Plot and illustration to show that depth to which light reaches in an EW grike 20cm wide and 200cm deep.

In appendix 1, a simulation illustrating light entering a 20cm wide grike was orientated EW and NS. The EW orientated grike received weak direct sun deeper than one metre at the start and end of the day, but little was absorbed by the grike walls before it reached even deeper due to the more indirect angle of light. At midday, a stronger light entered the grike, but the light struck the grike wall at a more direct angle, resulting in a greater proportion of energy being absorbed by the grike walls before the light reaches the bottom (Figure 4.27). This indicates why light intensity and temperature are consistently high over the day.

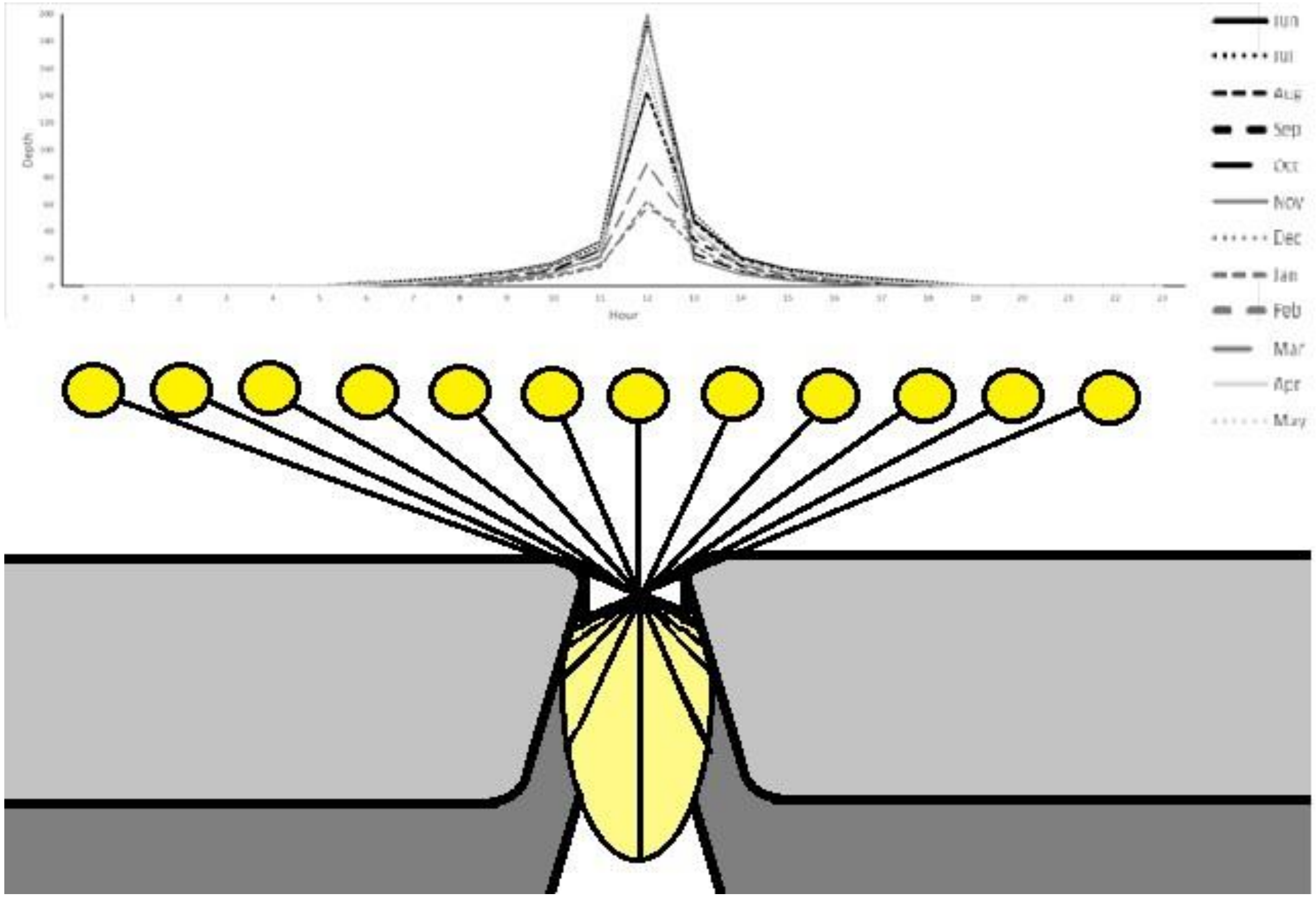


Figure 4.28 Plot and illustration to show that depth to which light reaches in a NS grike 20cm wide and 200cm deep.

NS grikes received light directly past one metre only during midday. Toward the start and end of the day, the light was weaker due to atmospheric attenuation and angle of incidence. This weaker light struck the wall of the grike where much of it was absorbed, resulting in less frequent and weaker indirect light reaching into the grike over the rest of the day (Figure 4.28). Based on this explanation, it can be understood why light intensity and temperature recorded in the NS grike is lower than that in the EW grike for most of the day, but higher at midday.

Appendix One simulated the light penetrating the grike over a year, showing that the depth to which direct light could penetrate was at a maximum during summer and a minimum in winter. During summer and winter, most of the direct light affected the top 50cm of a grike explaining the large amount of light observed in the upper zone of the grike. During winter, no direct light entered the 20cm wide simulated EW grike past 50cm, whereas the simulated NS grike received direct light past 50cm for around two hours per day. This may explain why the light intensity in the NS grike was higher than that in the EW grike in winter at a depth of 125cm.

These simulations have shown light entering a perfectly smooth-sided grike and serve to illustrate the potential extent of a light beam. In reality, many grikes are pitted, jointed and sometimes stepped (Vincent, 1995) which may result in different areas of light and shade.

4.3.3.3 Subsection conclusion

This subsection has solidified the link between temperature and light intensity, showing that the seasonal and diurnal cycles in both metrics are unlikely to be independent and correlate strongly. These findings build upon the conclusions of Subsection 4.3.2 by providing a likely causal relationship between the effects of month and hour on the temperature within a grike. This information is used in Chapter Six to inform the creation of the temperature simulation.

Orientation has been introduced as a possible variable to be considered in the temperature simulation in Chapter Six. The relationship between grike orientation and other variables such as depth and season are complex and appear to rely heavily on the interaction with light.

The zonation within the temperature and light intensity in the grike may be partly explained by the increased direct light incident on the upper 50 cm of the grike. The increased direct light may explain why the light intensity is considerably higher within this zone and why Subsection 4.3.2.2 shows the rate of temperature change within this region to be comparatively high.

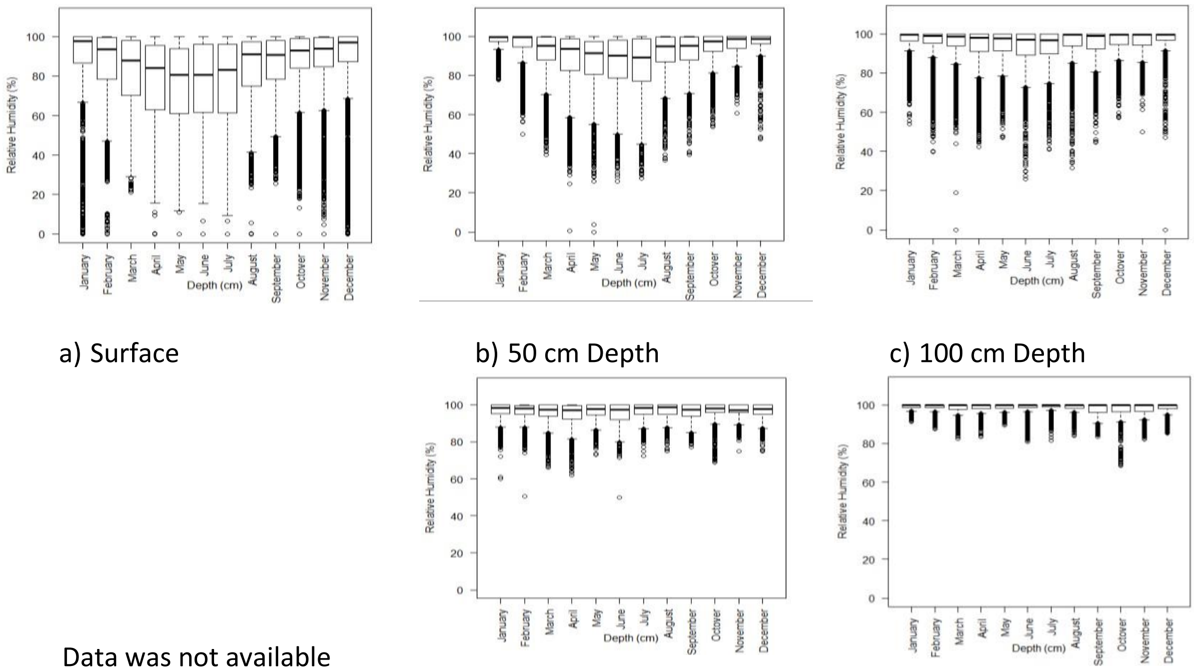
4.3.4 Relative humidity

In combination with light intensity and temperature, relative humidity influences the living environment for species found in the grike. The relative humidity is the least well-understood aspect of microclimate recorded in grikes. Thus far, only four studies known to the author have substantively referred to the relative humidity in grikes (Heslop-Harrison, 1960; Dickinson, Pearson & Webb, 1964; Burek & Legg, 1999; Alexander, Burek, & Gibbs, 2007). This measurement was most susceptible to anomalous results, and the data has required cleaning to produce a data set which can be used for analysis. The data from the loggers set at a depth of 150cm on the Fanore site is not available for analysis; as the loggers were not operational for a long enough time to retrieve the required amount of data.

4.3.4.1 Periodicity by month and by hour

4.3.4.1.1 Relative humidity over a year

The data were subdivided by month and by the hour in order to identify whether relative humidity shares similar periodicity alongside temperature and light intensity. Figure 4.29 shows the impact of seasonality on relative humidity.



a) Surface b) 50 cm Depth c) 100 cm Depth

Data was not available

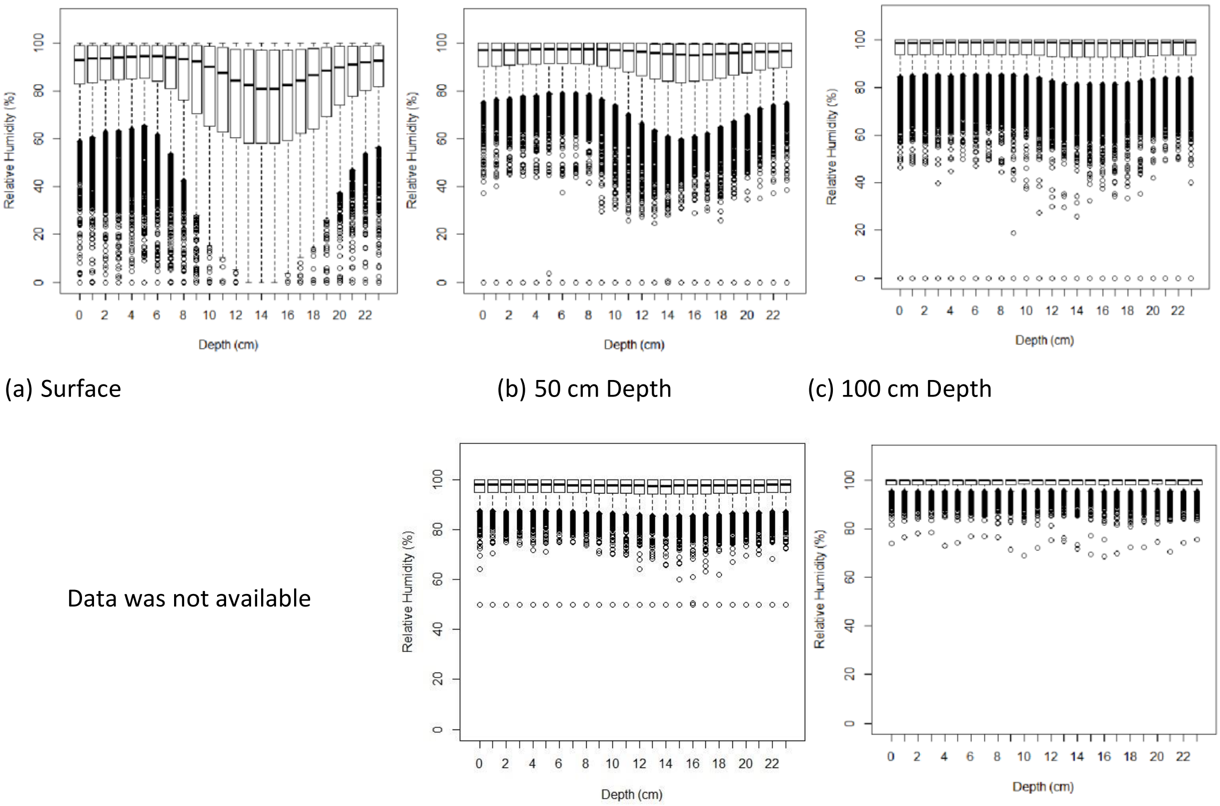
d) 150 cm Depth e) 200 cm Depth f) 300 cm Depth

Figure 4.29 Boxplots showing the cycles of relative humidity data taken over a year, from all grikes in this study.

The season has an influence on the percentage relative humidity found within the grike; this influence decreased with depth. During winter, the relative humidity of the grike and at the surface was very close to 100%; this is much more humid than the median relative humidity of the macroclimate which is typically 85-88% over the winter period in the regions of this study (Jenkins, Perry & Prior, 2008). The spread of relative humidity values was low compared to other times of the year, but there were a great number of outliers. The levels of relative humidity observed in the grike indicate that during winter, the grike stays very humid but can experience infrequent dryness. The surface of the grike during summer had a lower % relative humidity; however, the median was still high compared to the macroclimate which is typically 76-82% over the summer period in the regions of this study (Jenkins, Perry & Prior, 2008). The spread of the data was extremely high, and the 95th percentile included almost the entire range of relative humidities. At the surface, a decrease in relative humidity occurred more rapidly over spring than the decline in relative humidity during autumn.

Between the surface and 100cm, the difference between the relative humidity of the air and 100% relative humidity halved every 50cm into the grike, irrespective of the season. This decrease means that the relative humidity recorded at 50cm and 100cm resembled that at the surface, but are much higher. At a depth of 200cm and 300cm, the relative humidity was almost consistently at 100% and the season had very little impact on this.

4.3.4.1.2 Relative humidity over a day



(a) Surface (b) 50 cm Depth (c) 100 cm Depth

(d) 150 cm Depth (e) 200 cm Depth (f) 300 cm Depth

Figure 4.30 Boxplots showing the cycles of relative humidity data taken over a day, from all grikes in this study.

In figure 4.30, at the surface of the grike, there appears to be a periodic fluctuation in relative humidity. The relative humidity in the grike was highest around dawn, at which point the distribution of the data was very restricted (Figure. 4.31). The relative humidity was lowest, and the distribution of the data became broader toward midday. The rate of change in relative humidity between dawn and midday was comparable to the rate of relative humidity change between midday and dusk; however, from dusk, the relative humidity increased more gradually until dawn.

The magnitude of the fluctuation in relative humidity decreased with depth, and the relative humidity became more stable and more humid. Lower depths of the grike remained very close to peak relative humidity for long periods of the night and some of the daytime.

4.3.4.2 Relative humidity and orientation

It is possible that orientation could influence the relative humidity of a grike through the action of the solar heat evaporating the water to dry the soil. Orientation could also influence the air movement in grikes by altering the direction and power of the wind flowing over the surface. This topic is explored in greater detail in Chapter Five.

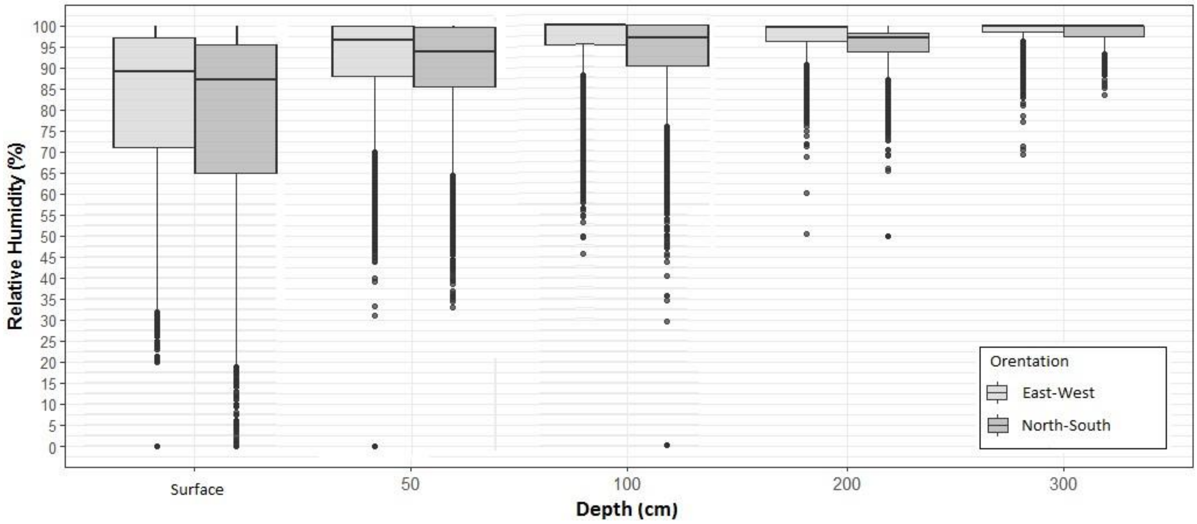


Figure 4.31 Boxplots showing the difference in relative humidity between all NS and EW grikes used in this study.

By comparing the NS and EW grikes, it can be observed that the EW grike was slightly higher in relative humidity than the NS grike, and this remained consistent for all grikes in this study (Figure. 4.30).

4.3.4.3 Subsection conclusion

The recording and analysis of relative humidity data have produced several insights which are comparable to other areas of this study. The relative humidity was similar over all years and in all pavements. There were, however, only minimal differences between grikes of differing orientation. The influence of depth on the relative humidity of grikes in this study has characteristics shared by both light and temperature. The relative humidity of the grike becomes less variable as depth increases, but unlike other measures of microclimate in this study, the relative humidity increases as depth increases. The comparison of a grike to a forest is further bolstered by the comparative similarity of the two environments. In temperate forests, a temperature gradient has been observed spanning over 240 metres (Chen, Franklin & Spies, 1995), but also to have been influenced by orientation due to the impacts of wind rather than the impact of insolation (Chen, Franklin & Spies, 1993). In studies of forest microclimate, relative humidity has been seen to have the shallowest gradient of change from edge to the interior, when compared to temperature and light intensity (Gehlhausen, Schwartz & Augspurger, 2000). This indicates that distance into the forest has the least impact on the relative humidity when compared to other microclimate variables. The observations in forests are in contrast to what has been observed by this study where relative humidity increases very rapidly with distance from the surface and becomes far more stable than temperature or light intensity.

Cave microclimate studies have indicated that relative humidity is almost constantly high and paralleled temperature in gradient (Hall, 1982). In one such study the interior chambers of caves are constantly above 94% and reach a minimum 50% relative humidity only in the summer in the cave exterior mouth (Hoyos et al., 1998). The relative humidity of caves is attributed to the large amounts of free-flowing or pooled water available in caves, and in some caves, bats influence the microclimate (Baudunette et al., 1994). The observations in caves are in contrast to grikes, where free water is rare, and much of it is absorbed by plants or drains through the soil (Trudgill, 1985). It has however been proposed in Subsection 4.3.1.3 that water in the substrates at the bottom of grikes may provide a local source of evaporating water to maintain relative humidity at the bottom of grikes (Yarranton & Beasleigh, 1969).

The long-term study of the relative humidity of limestone pavement grikes has produced several findings which may be advanced upon to influence the management of limestone pavements in the future. The relative humidity in grikes of this study increases close to 100% within very little distance from the surface, showing that even shallow grikes may maintain high relative humidity in the event of a warmer climate.

4.3.5 Severe weather events

An increasing number of severe weather events are being attributed to the change in global climate (Fischer & Knutti, 2015) and a general increase of atmospheric storminess around Britain and Ireland is increasing the probability and severity of storms (Bengtsson, Hodges & Roeckner, 2006). Thermally sheltered habitats such as grikes have been shown to reduce the effect of temperature extremes (Stevenson, 1985) which could potentially reduce biodiversity by causing population crashes in response to unusual weather conditions (Jentsch & Beierkuhnlein, 2008; Orsenigo, Mondoni, Rossi & Abeli, 2014).

During this data collection, there were several events which have been considered by the Met Office to be severe weather events in Great Britain and one event of interest to this study which was considered severe by Met Éireann (Met Éireann, 2018; Met Office, 2017). Three weather events in Great Britain were chosen for further study, the early 2013 spring cold, the 2013 heatwave and the 2015 flooding. For each event, data were gathered for the month of the event and one month before and after. Data was taken only from the Holme Park Quarry site in Great Britain because this site was the only site in this study to be established for the duration of all three events and was also geographically relevant to all three events. In the Republic of Ireland, only the Fanore site was used because this had particular relevance to the coastal flooding event which took place during the study.

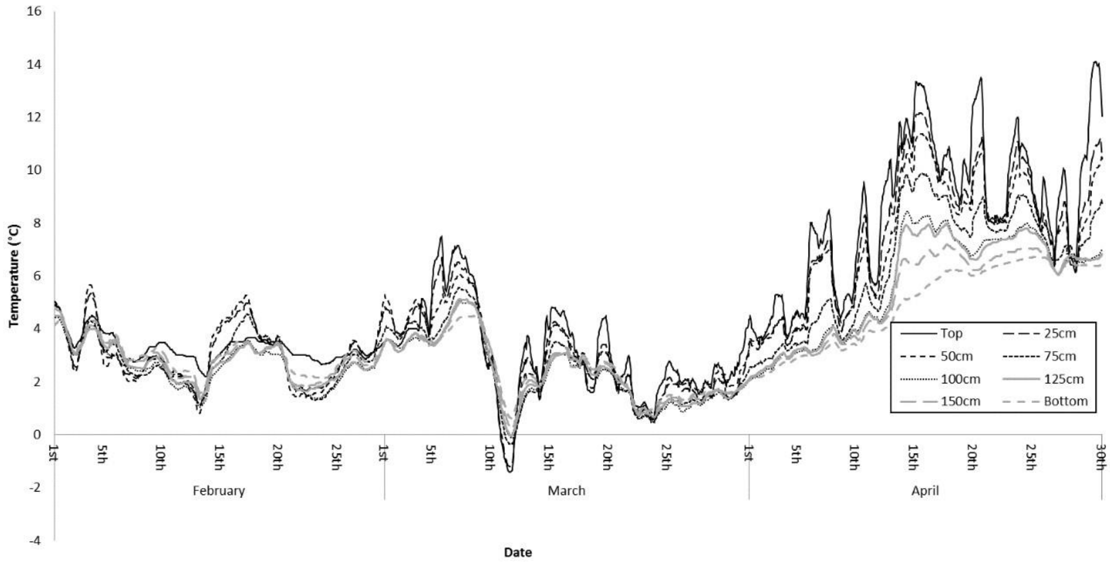
The limited number of severe weather events and limestone pavements studied in this subsection makes it unlikely that all conditions and impacts on limestone pavements' microclimate have been accounted for, and therefore require further study in order to understand more fully. However, Subsection 4.3.1 indicates that while each site has unique elements, the underlying patterns in the microclimate's reaction to changes in macroclimate is similar. By this logic, it may be said that the impacts of severe weather on grikes may vary with the external conditions and internal grike structure, and the observations of this subsection may provide guidance to discern the likely impacts to the microclimate.

4.3.5.1 Snow and low temperature

Great Britain experienced below-average temperatures in 2013 from the 10th March to the 10th April due to winds from Northeast Europe and Siberia. Combined with persistent cloud cover and snowfalls, the weather of March and early April of 2013 was very cold for the time of year. The coldest period for Great Britain over this period was reported to have been from the 22nd to 24th March when widespread snow fell and reached 20mm in places which remained on higher ground until early April (Met Office, 2017b). Over the same period, weather records in Carran on the east of The Burren recorded the lowest temperatures throughout this study. The minimum temperature in Carran at this time was -3.1; however, this period is not recognised as severe by Met Éireann and is not the coldest period recorded this decade. To provide context, the coldest period over this decade occurred in 2010, where temperatures reached -9.6 on Christmas day of that year (Met Éireann, 2018).

4.3.5.1.1 Temperature

NS



EW

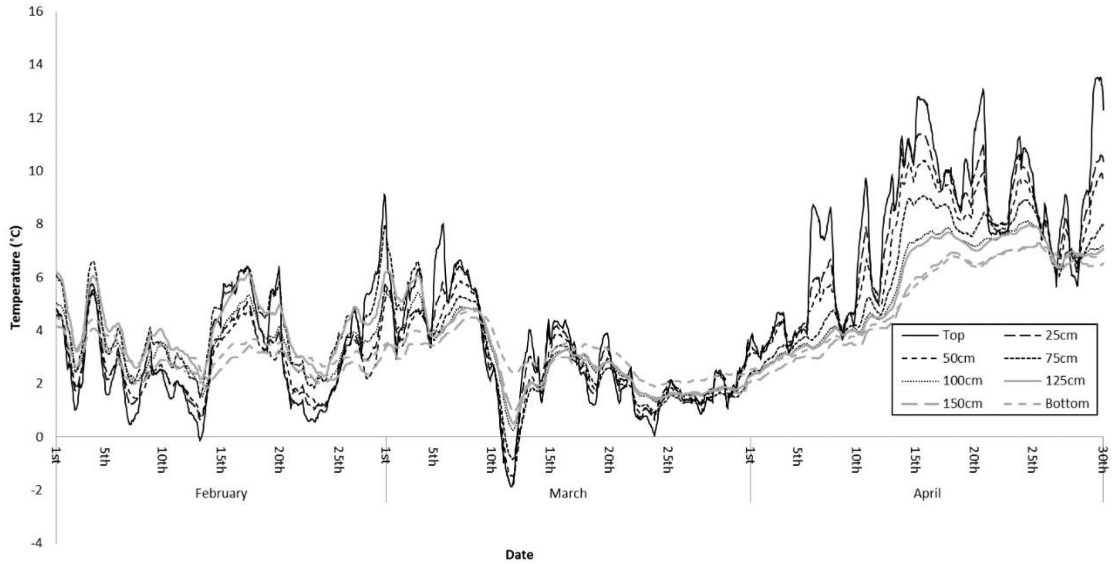
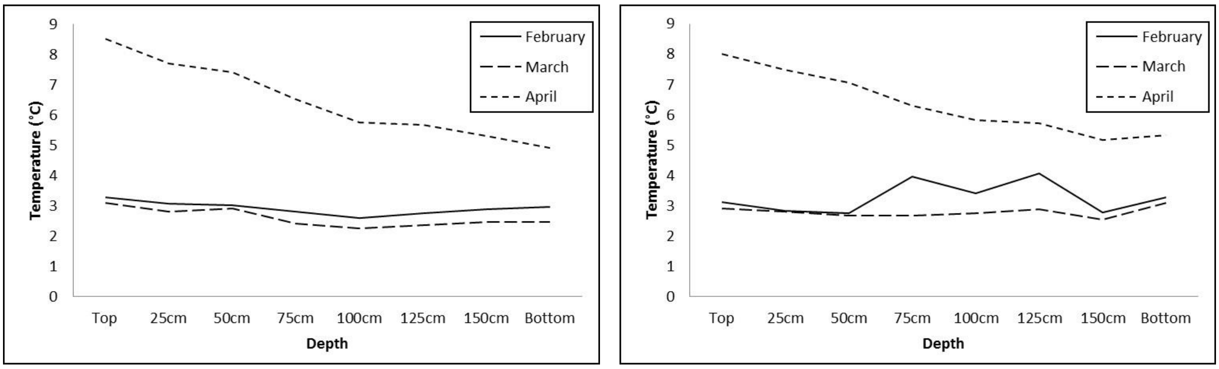


Figure 4.32 Temperature taken from NS and EW grikes on the Holme Park Quarry site during the low-temperature period.

Figure 4.32 shows the temperature in the NS and EW grikes during an unseasonably cold March. In both orientations, there were several temperature inversions during February where the temperature at the surface rose above and fell below that of the bottom of the grike, which caused the temperature at other depths to change similarly. This influence appeared far more pronounced in the EW grike when compared to the NS grike. During the March cold period, the temperature in all areas of the grike in both orientations was consistently below 5 °C from the 10th March onward.

There were two cold periods, a very cold short period around the 12th March and a longer mildly cold period from the 20th to the end of March. The surface temperature during the first period dropped sharply below 0°C; however, the impact on the temperature at the bottom of the grike was equal to or less than the milder extended cold period. The second period exhibited a more extended dip in surface temperature that never dropped below 0°C, and the temperature at the bottom of the grike dropped lower than it did during the first cold period. When comparing grike orientations, the temperature recorded at the surface in both grikes appeared similar; however, as depth increased, the temperature became more stable in the EW grike than the NS grike. Despite being more stable in the EW grike, the average temperatures for both grikes in March were similar at around 3 °C as can be seen in Figure 4.32. In Figure 4.33, it can be seen that the temperature at the bottom of the EW grike was around half a degree warmer than at 150cm; this effect was not seen in the NS grike. In April, the temperature at all levels of the grike began to climb. Figure 4.33 shows that at this point it was warmer closer to the surface of both grikes and temperature decreased with depth. The temperature was more variable at the surface, and there was a short time delay between warming at the surface and each subsequently deeper temperature recorded.

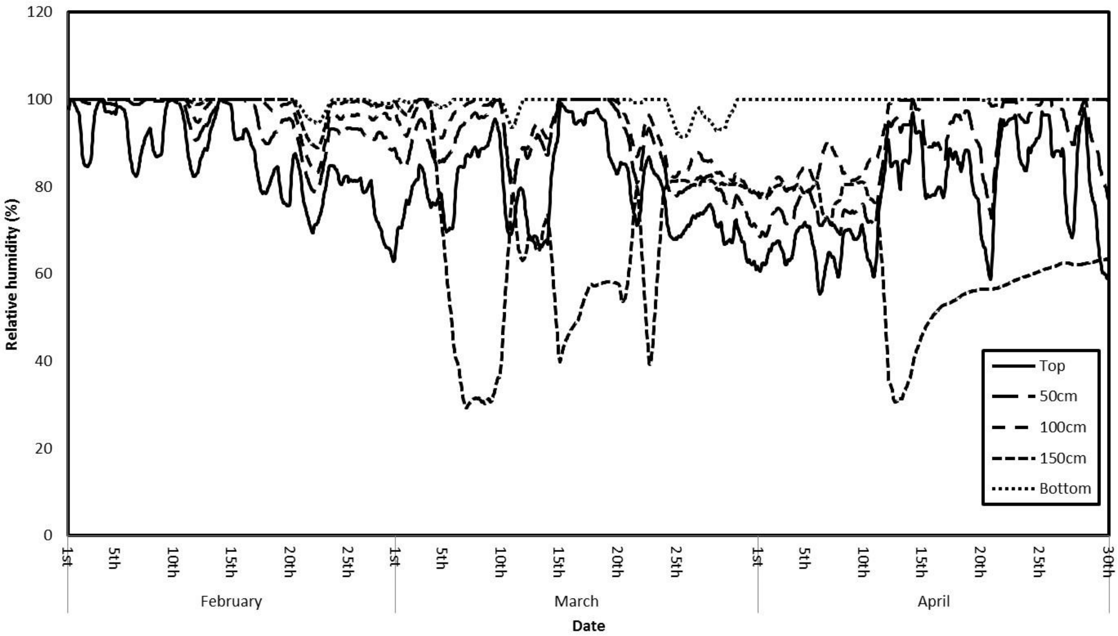


NS EW

Figure 4.33 Mean temperatures taken from NS and EW grikes on the Holme Park Quarry site during the low-temperature period.

4.3.5.1.2 Relative humidity

NS



EW

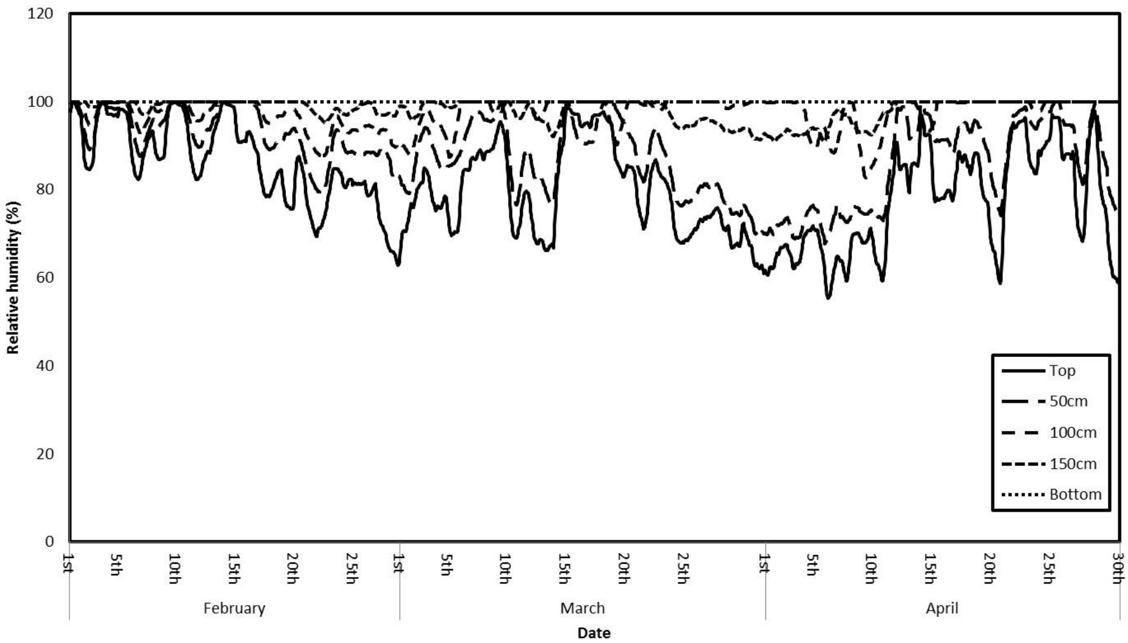
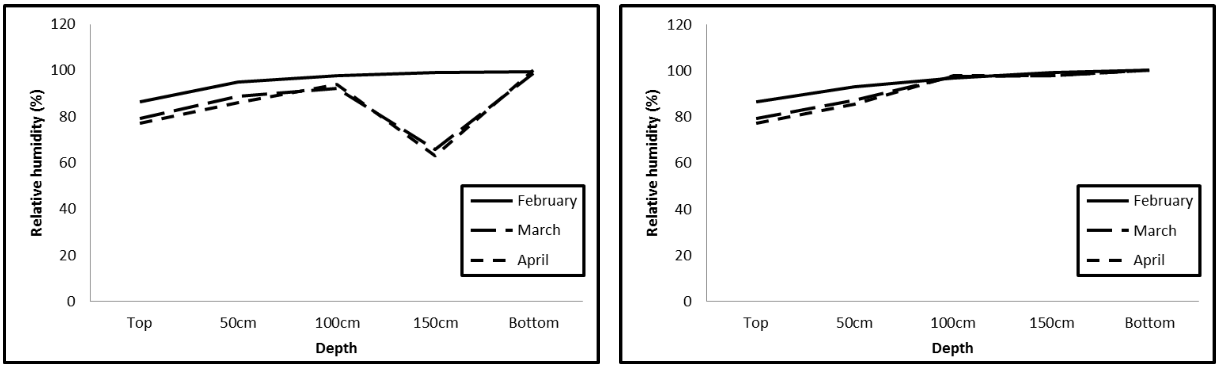


Figure 4.34 Relative humidity taken from NS and EW grikes on the Holme Park Quarry site during the low-temperature period.

Figure 4.34 shows that relative humidity in both grikes fluctuated a small amount during February. These fluctuations in relative humidity decreased with depth and the relative humidity increased as depth increased. During the colder than average March, it was possible to identify two periods of high relative humidity (5th to 10th and 15th to 20th March) which coincide with the periods which were warmer. The intervening period from 10th to 15th March was both very cold and lower in relative humidity within the upper areas of the grike. After the 20th March, there was a period of decreasing relative humidity in the upper areas of the grike which coincides with warming temperature and the period within which the Met Office reported lingering snow. Both grike orientations have shown a similar set of results as can be seen in Figure 4.35 the exception to this was the data gathered at 150cm in the NS grike. This data varied wildly and has often shown an opposite trend to all other data.



NS EW

Figure 4.35 Mean relative humidity taken from NS and EW grikes on the Holme Park Quarry site during the low-temperature period.

4.3.5.1.3 Snow and low-temperature implications

During the cold period explored in this subsection, there were two cooling events, one short and intense and one long and less intense. Both reduced the grike temperature but in differing ways. This phenomenon can be explained by exploring the principles of the heat capacity and density of the limestone in the pavement, which together express the thermal mass of the system (Serway & Jewett, 2012).

In Subsection 4.3.2 the grike microclimate was hypothesised to be influenced by two main forces, one from above destabilising the temperature and another from below stabilising the temperature. The probable influence of the limestone of the clint is discussed and how this provides the stabilising influence during severe cold. Heat capacity is the amount of heat energy required to raise the temperature of a system by 1°C. The heat capacity of limestone is 0.84 (Robertson, 1988), making it not as good at absorbing heat as metals, but better than more insulating materials such as wood.

The density of limestone is such that it can hold on to large amounts of absorbed heat energy (Serway & Jewett, 2012). These two factors combined to provide limestone with a high thermal mass. The high thermal mass of limestone is the reason it is commonly used as part of a hearth or fire surround, to absorb heat while a fire is lit and radiate heat slowly as it cools. Within the grike, it is possible to see this property of limestone in action. The limestone of the clints has absorbed heat energy from the sun and retains a fraction of the heat absorbed. It can be seen in Figure 4.36 that between the 10th and 12th of March, the temperature outside the grike dropped rapidly reducing the input of heat energy to both the grike and clint for a short period. Due to the high thermal mass, the limestone clint lost heat energy more gradually than air; partly explaining the higher temperature deep in the grike over this period.

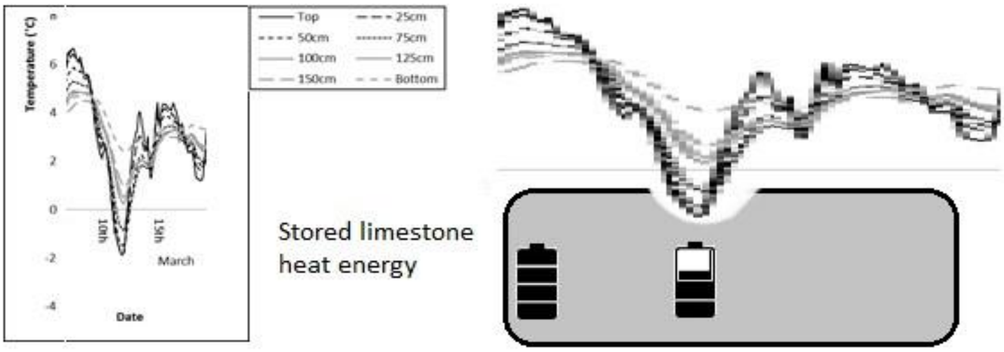


Figure 4.36 Illustration to explain how heat energy is stored in the limestone during a cold snap.

After this cold snap, the temperature rose to allow the air and limestone clint to absorb more heat energy. It is shown in Figure 4.37 that later, between the 17th and 25th of March, the temperature outside the grike dropped again. This time the decrease in temperature was not as great as previously recorded, but it occurred over a longer period. Despite the decrease in temperature at the surface being of less magnitude when compared to the previous cold snap, the temperature at the bottom of the grike dropped just as much if not more. This could have been because the heat energy absorbed by the limestone was once more being released but over a longer period. Reducing the amount of stored energy to the point where it was no longer supporting the temperature in the grike to as great a degree.

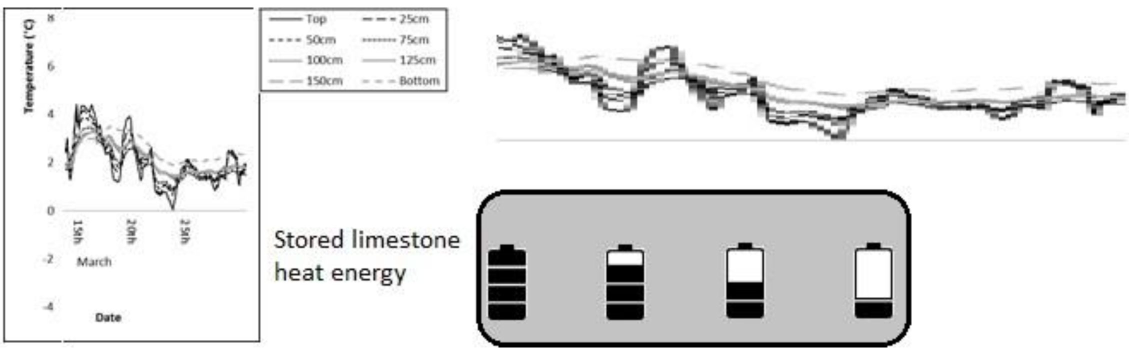


Figure 4.37 Illustration to explain how heat energy is stored in the limestone during a steady cold period.

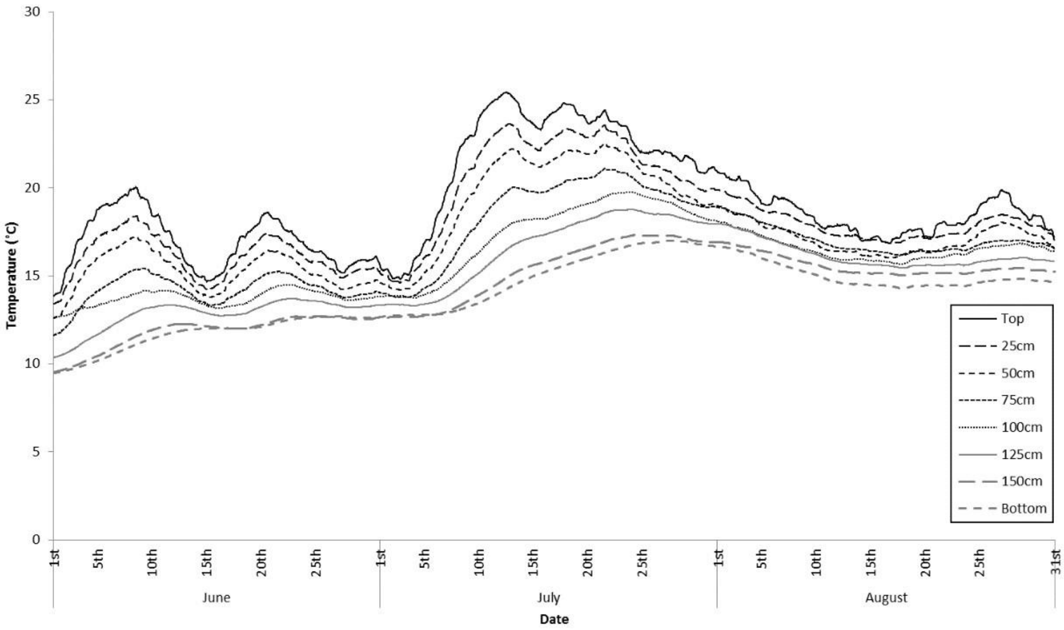
During the severe cold, the relative humidity in the grikes drops as a response. Air that is cooled to below 0°C can hold only a small amount of water vapour and is therefore low in absolute humidity. When this drier air is warmed inside the upper zone of the grike, the absolute humidity may remain similar to that of the outside but now have a lower relative humidity as explained in Subsection 4.2.2.3.2. As depth increases, the higher availability of free water causes the air to become more humid, which results in a gradually higher relative humidity from the surface of the grike to the base.

4.3.5.2 Drought and high temperature

During the summer of 2013, there was a period of high temperature throughout Great Britain and Ireland. The drought was characterised by almost unbroken sunshine and temperatures in Great Britain, exceeding 28 °C in many areas every day from the 13th to 19th July (Met Office, 2017b). In Great Britain, this was reported as a severe weather event by the Met Office (2017b). However, Met Éireann did not consider this summer to be a severe heatwave or drought. For context, the weather station at Carran recorded temperature maximums of 18.6°C to 28.1°C over the same period, but similar temperatures occur over the same period within the last decade. The Burren also has periods of greater drought than were experienced in this study, for example from 1982 to 1984 the total of rain which fell in July was equal to that which fell in July of 2013 (Met Éireann, 2018a).

4.3.5.2.1 Temperature

EW



NS

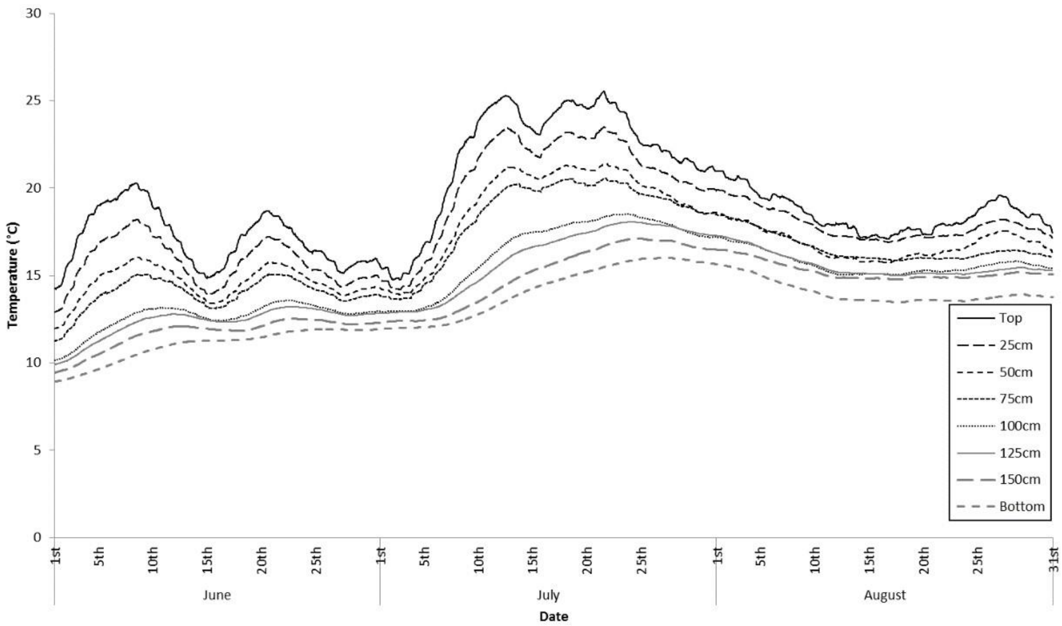
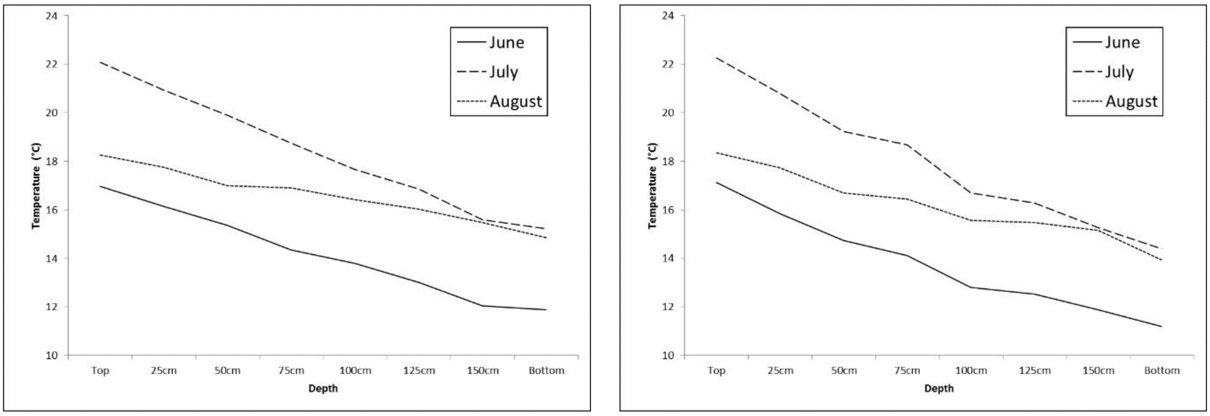


Figure 4.38 Temperature taken from NS and EW grikes the Holme Park Quarry site during the high-temperature period.

The impact of the heatwave during July of 2013 had a very similar impact in both orientations of grike as shown by Figure 4.38. The temperature rose more rapidly than it decreased, and there was an observable delay in temperature change between surface and grike as predicted in Subsection 4.3.2.3. These two factors may have resulted in the increasing disparity between recorded grike temperatures taken at different depths as the temperature increased, however as temperature decreased, this difference reduced, and some levels of the grike became very similar. The disparity is exemplified in

Figure 4.39, which shows that as temperatures increased during June and July, there was a large range in temperature in the grike, whereas in August there were more similar temperatures recorded in the grike as the temperature decreased.

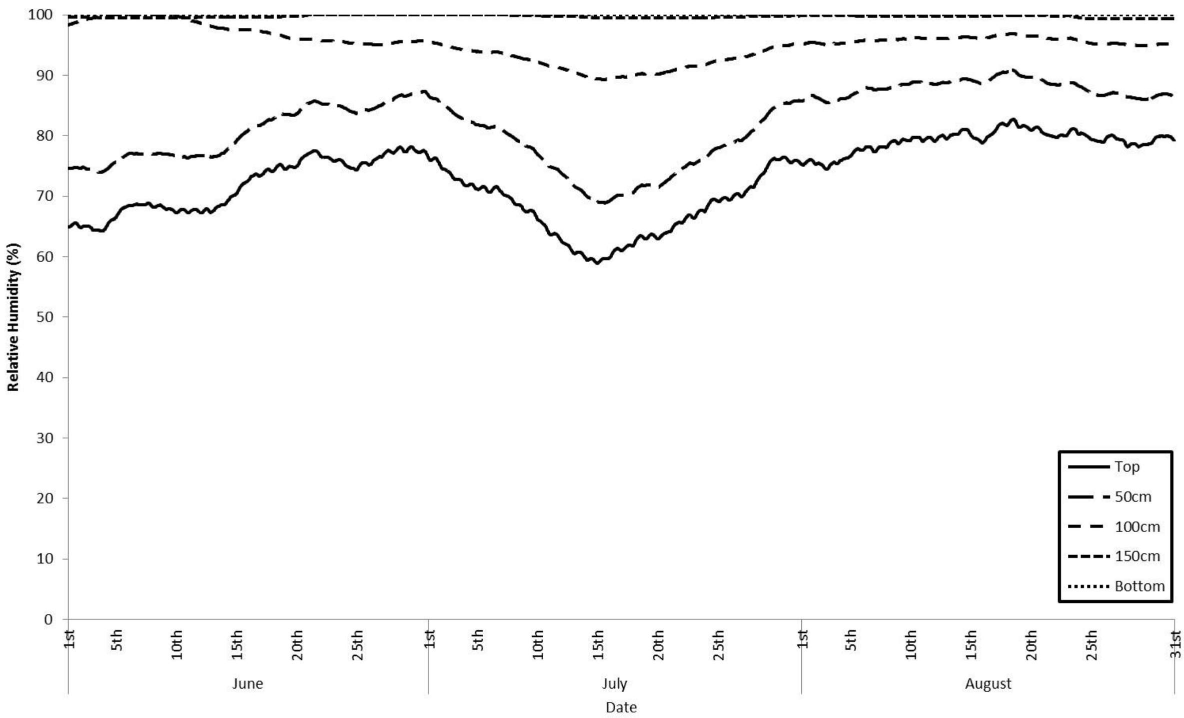


EW NS

Figure 4.39 Mean temperature taken from NS and EW grikes on the Holme Park Quarry site during the high-temperature period.

4.3.5.2.2 Relative humidity

EW



NS

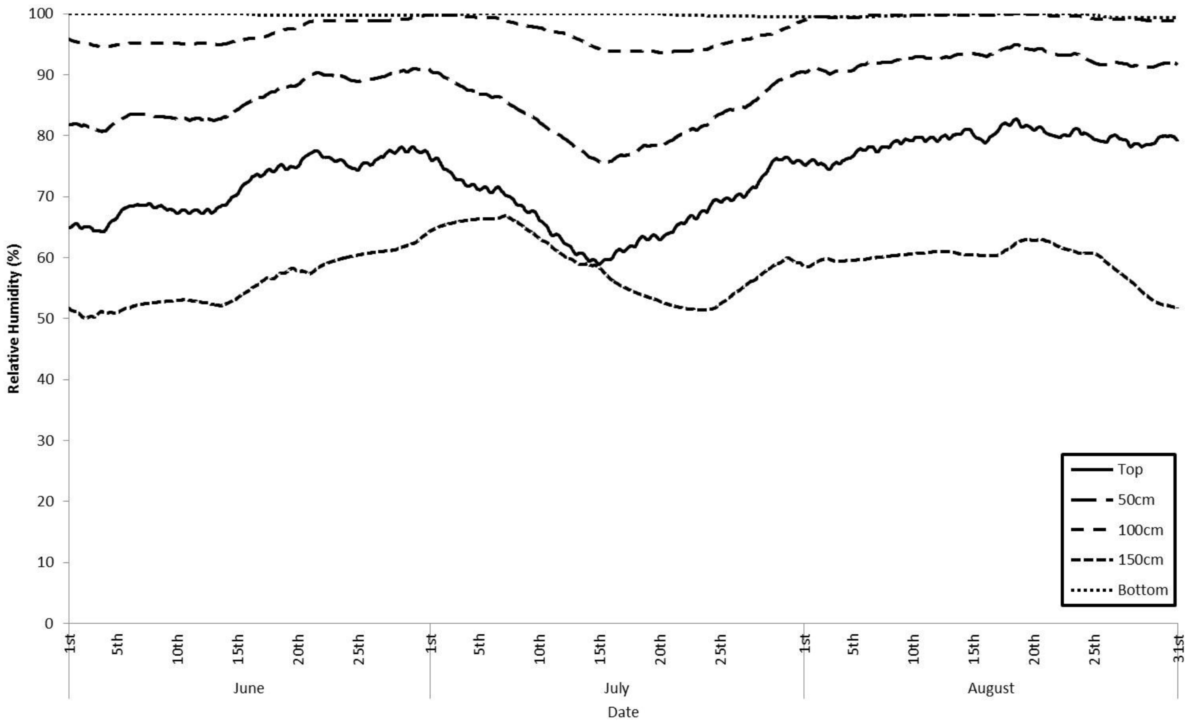
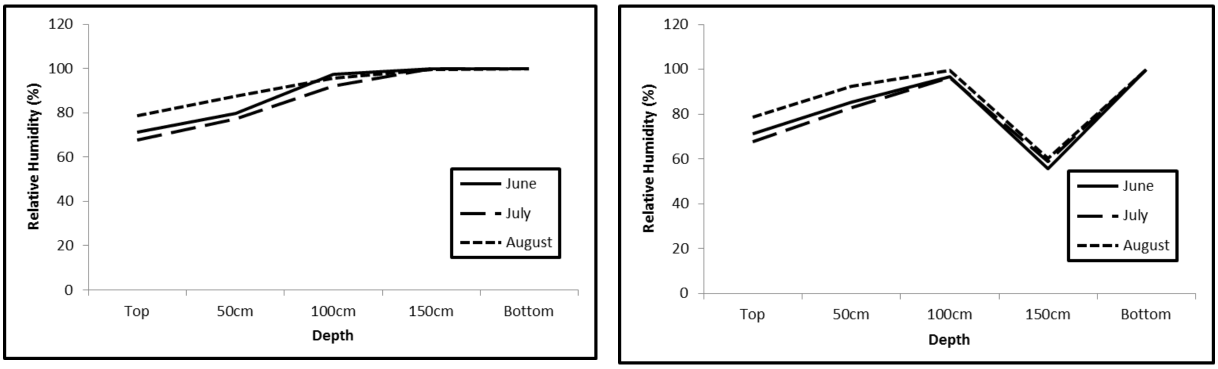


Figure 4.40 Relative humidity taken from NS and EW grikes on the Holme Park Quarry site during the high-temperature period.

The patterns in the relative humidity of both grikes shown in Figure 4.40 were very similar, except the data from 150cm in the NS grike, which recorded relative humidity far lower than was expected over the period. In June the Met Office (2017) described increasing precipitation and thunderstorms toward the end of the month, resulting in a gradual increase in relative humidity at all levels of the NS grike. Figure 4.41 shows a similar set of average relative humidities for each grike and month, with the exception, mentioned previously.

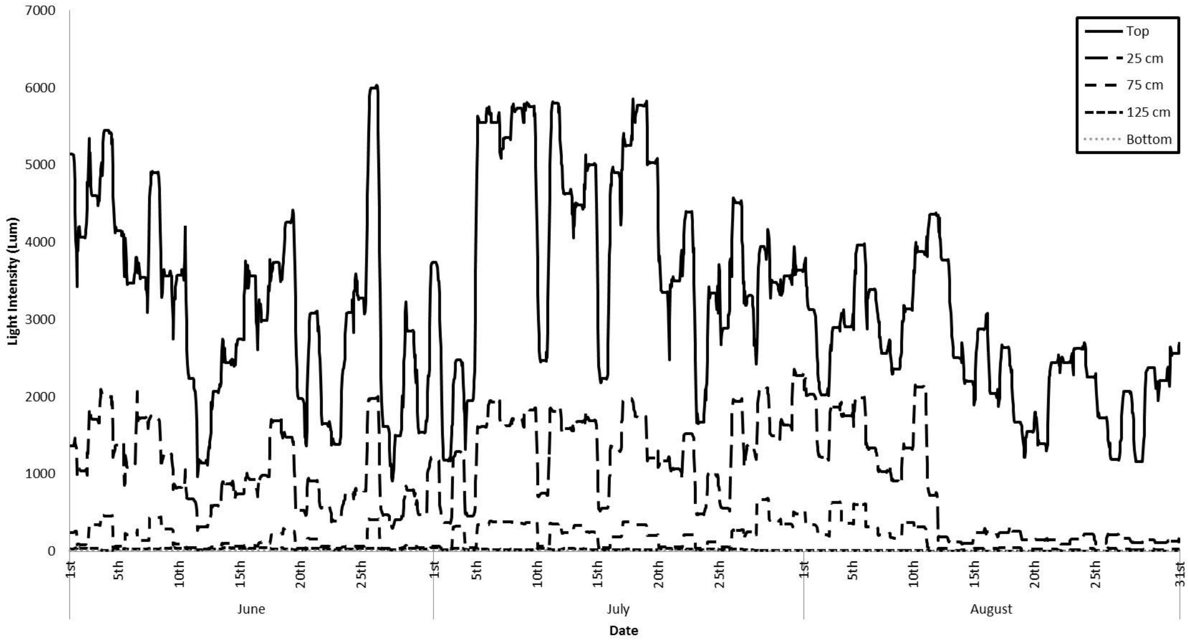


EW NS

Figure 4.41 Mean relative humidity taken from NS and EW grikes on the Holme Park Quarry site during the high-temperature period.

4.3.5.2.3 Light Intensity

NS



EW

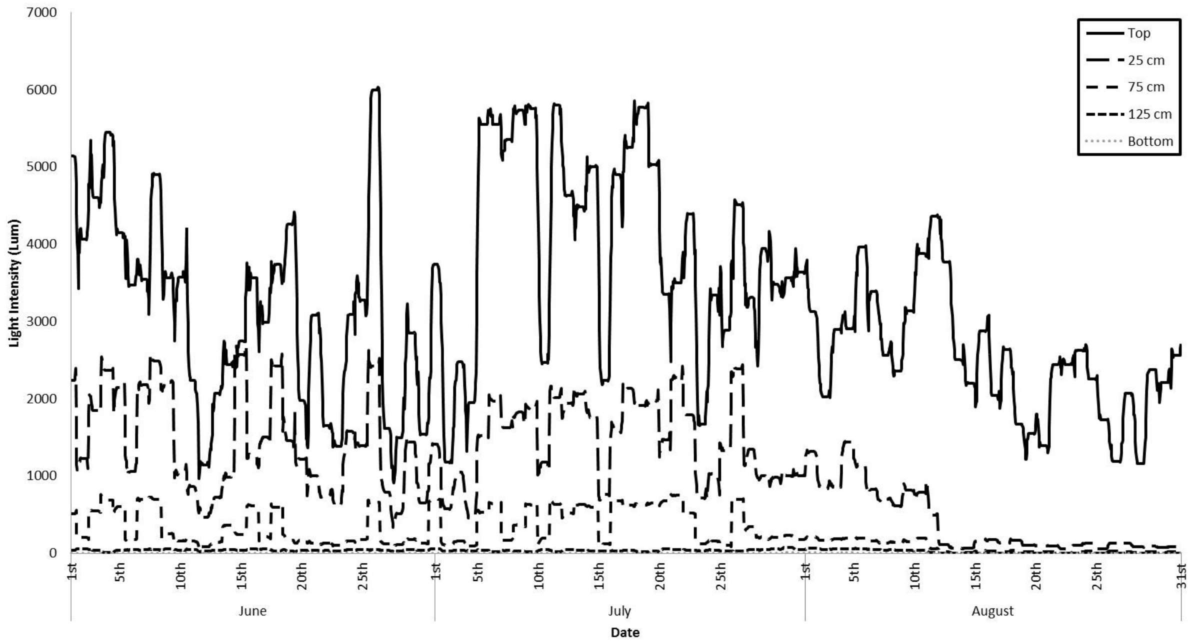
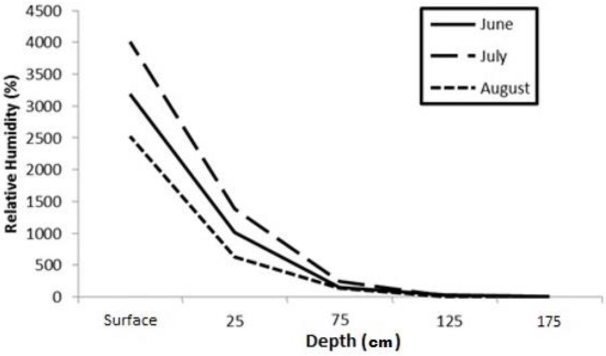
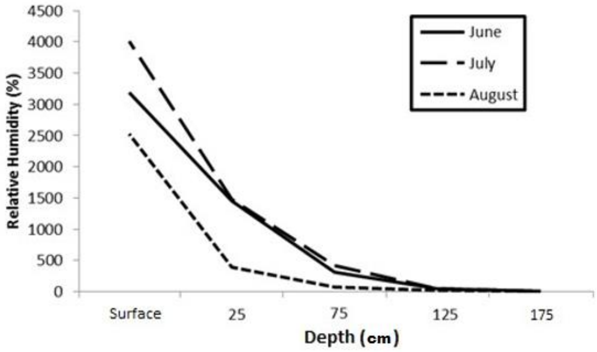


Figure 4.42 Light intensity taken from NS and EW grikes on the Holme Park Quarry site during the high-temperature period.

Both plots in Figure 4.42 show that the amount of light recorded during August of 2013 following the drought were very similar in both EW and NS grikes. During June and July, there was a disparity between the higher light levels observed in the EW grike and the lower light observed in the NS grike. This disparity occurred only between the depth of 25cm and 125cm. This fact and greater disparities between light in NS and EW grikes are discussed in greater detail in Subsection 4.3.3.





NS EW

Figure 4.43 Mean light intensity taken from NS and EW grikes on the Holme Park Quarry site during the high-temperature period.

4.3.5.2.4 Drought and high-temperature implications

This case study demonstrates the stabilisation observed in the grike, even in severe weather. The heatwave experienced by Great Britain provided a natural experiment, showing what happened to temperatures in the grike under severe weather of this region. The results of this indicate that even during the hottest summer, relative humidity was maintained in the grike and the temperature remained more stable at greater depth in the grike. So much so that the difference between surface and grike bottom temperatures reached over 10°C.

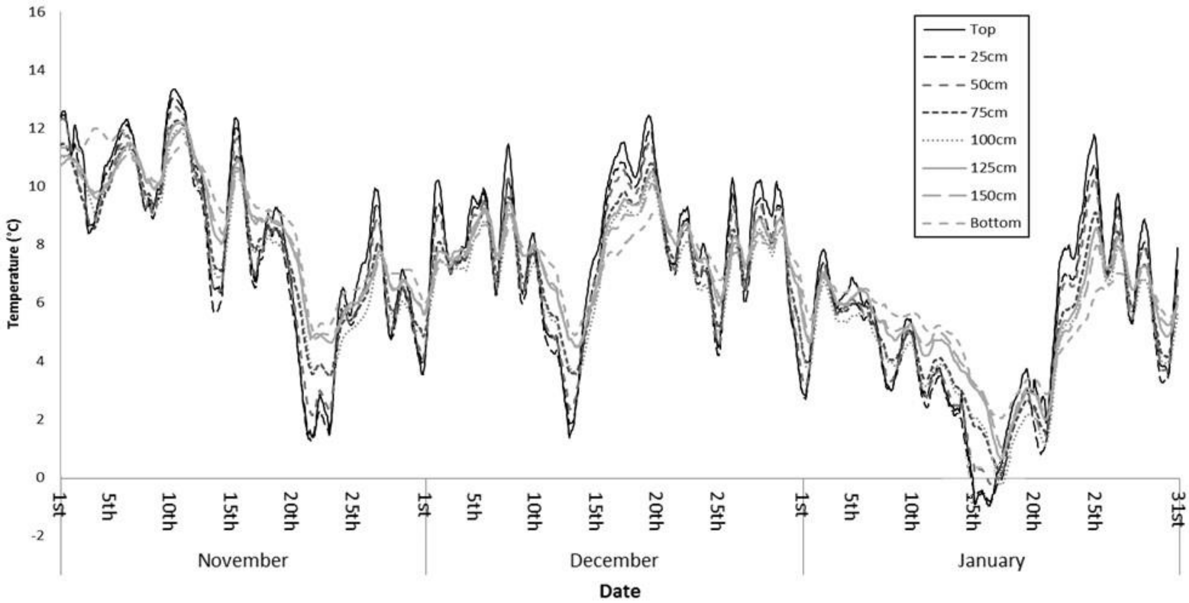
This natural experiment has also highlighted the delayed onset of temperature change within the grike observed in Subsection 4.3.2.3, and the abnormality in the temperature gradient between 0.75m and 1m in depth. Delays in temperature change have been observed on a much larger scale in caves, where external increases in temperature occur after a recordable delay due to the thermal inertia caused by the surrounding mountain (Badino, 2004). It is important to note that the temperature and relative humidity in the grikes do eventually change. These findings highlight that more drought-prone parts of Britain and Ireland may show a greater reaction to extended hot and dry climates and even the seemingly stable climates of caves and grikes are subject to climate change. This trend highlights the need for extended study in areas like The Burren to explore and monitor the effects of climate change.

4.3.5.3 High precipitation and storms

During December of 2015, the Met Office reported widespread flooding in northern Britain due to an excessively mild winter. The sustained period of wet weather set new records for precipitation over a calendar month, which were last set in 1910. Coupled with the impact of storm Desmond, areas of Cumbria received record-breaking daily total rainfall on the 4th and 5th December (Met Office, 2017b). During this period many parts of Co. Clare in the Republic of Ireland experienced extensive flooding including Corofin on the southeastern edge of The Burren. On most of The Burren there are no reports of flooding despite there being the largest amount of December rainfall since records of weather from Carran began in 1975 (Murphy, 2015; Independent.ie, 2015; Met éireann, 2018).

4.3.5.3.1 Temperature

NS



EW

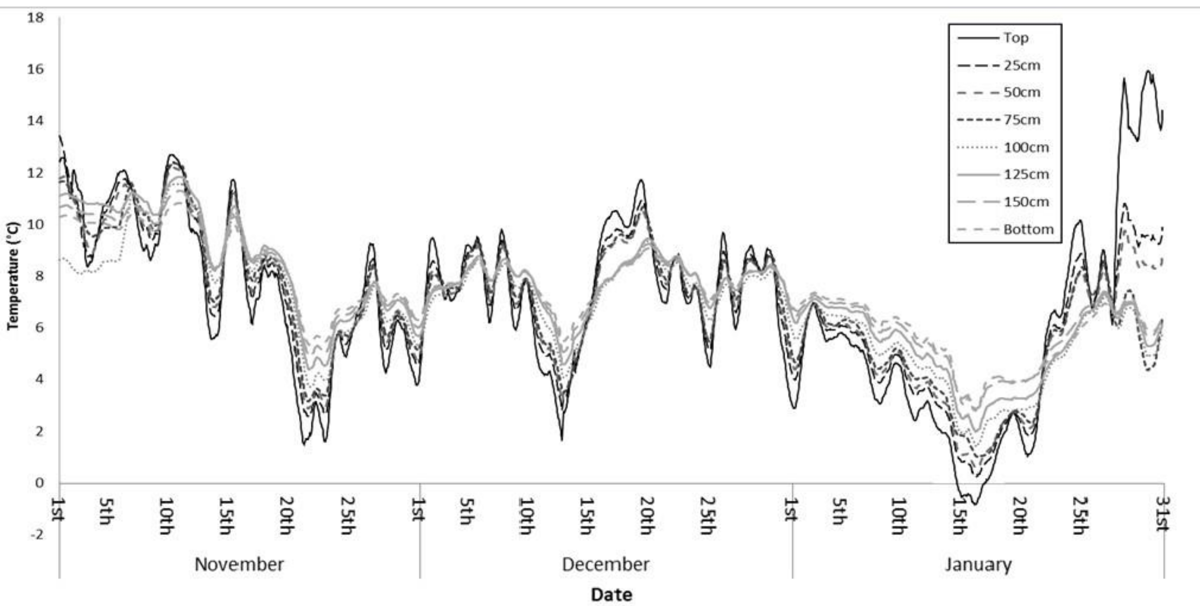
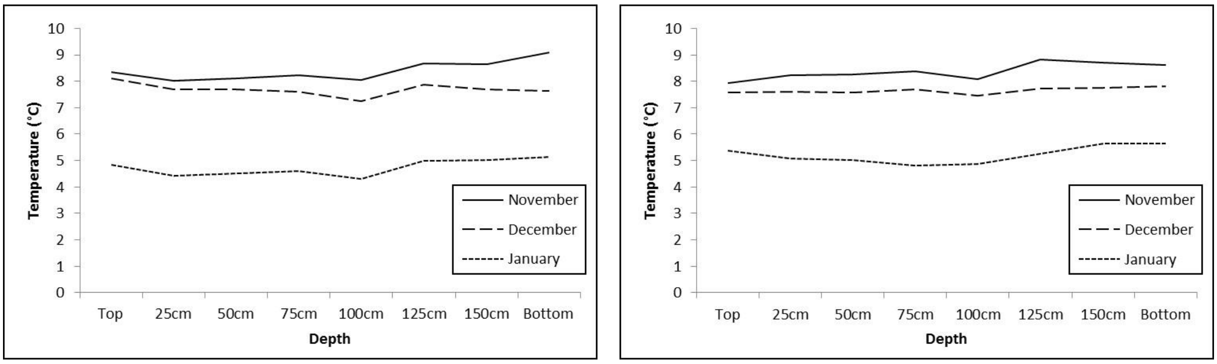


Figure 4.44 Temperature taken from NS and EW grikes on the Holme Park Quarry site during the wet period.

Figure 4.44 shows the temperature of the EW and NS grikes during the flooding that occurred in the winter of 2015 and early 2016. The temperatures recorded at all grike depths during this period more closely match the temperature at the surface than was observed during colder periods (Figure 4.43) or warmer periods in Figure 4.45. Figure 4.45 shows that the winter of 2015 was equally warm in both NS and EW grikes.

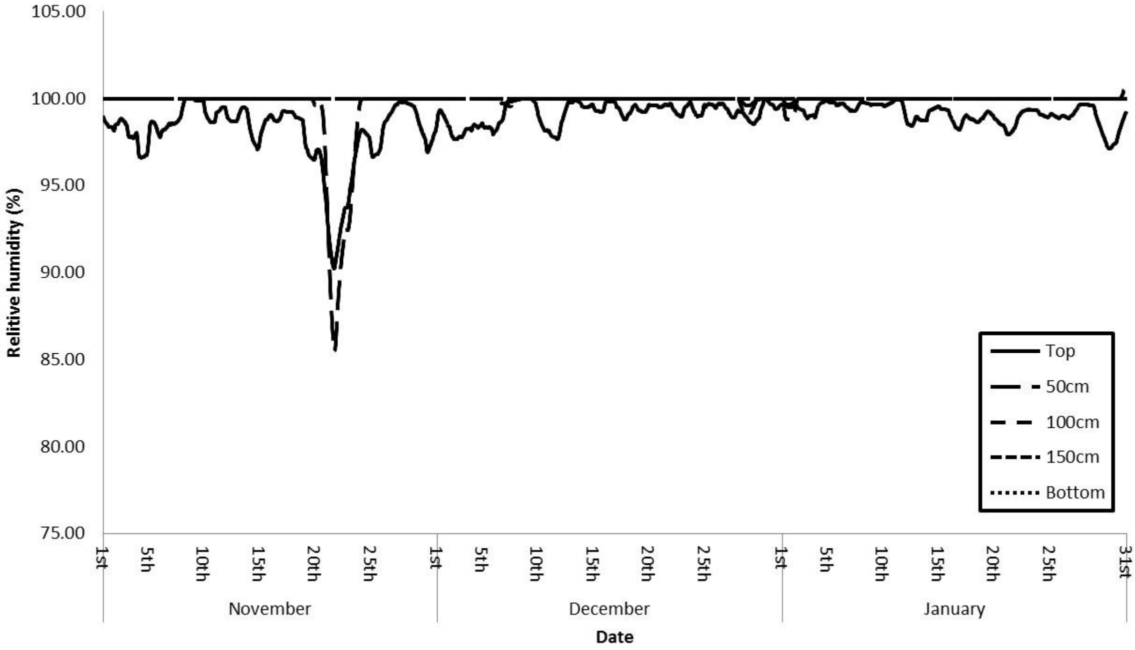


NS EW

Figure 4.45 Mean temperature taken from NS and EW grikes on the Holme Park Quarry site during the wet period.

4.3.5.3.2 Relative humidity (Holme Park)

NS



EW

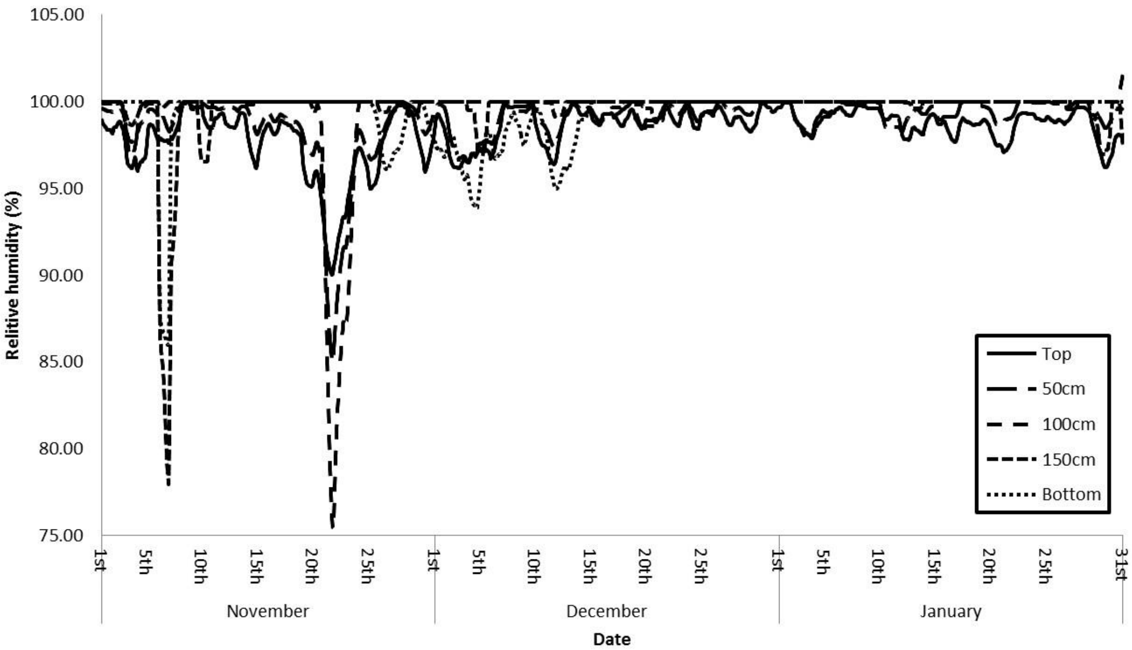
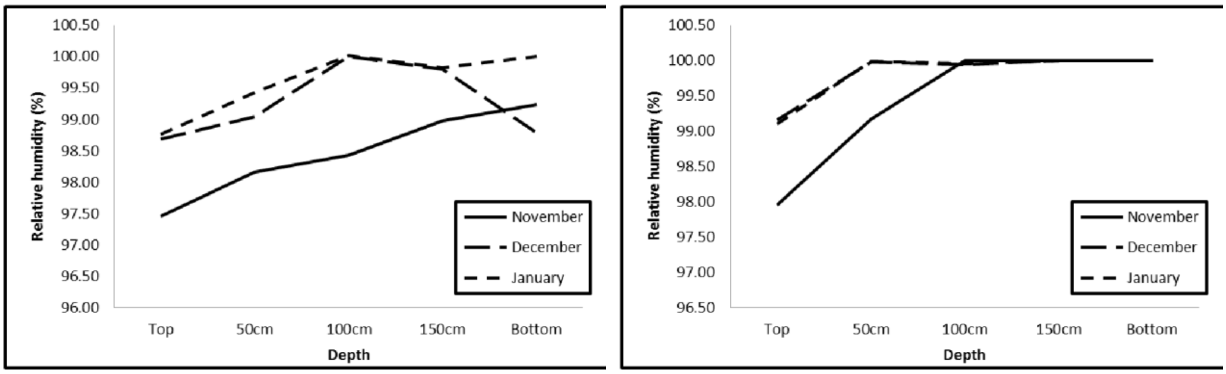


Figure 4.46 Relative humidity taken from NS and EW grikes on the Holme Park Quarry site during the wet period.

The relative humidity during the period of high precipitation in Figure 4.46 showed very little variation from almost 100% relative humidity. The exceptions to this was between the 5th and 10th of November in the EW grike where there was a short decrease in relative humidity and a similar decrease in both grikes between the 20th and 25th of November. Except for these two anomalies, there was very high relative humidity. The variation from 100% relative humidity below 50cm is higher in the EW grike; however, this rarely dipped below 95%. These trends can also be observed in Figure 4.47.



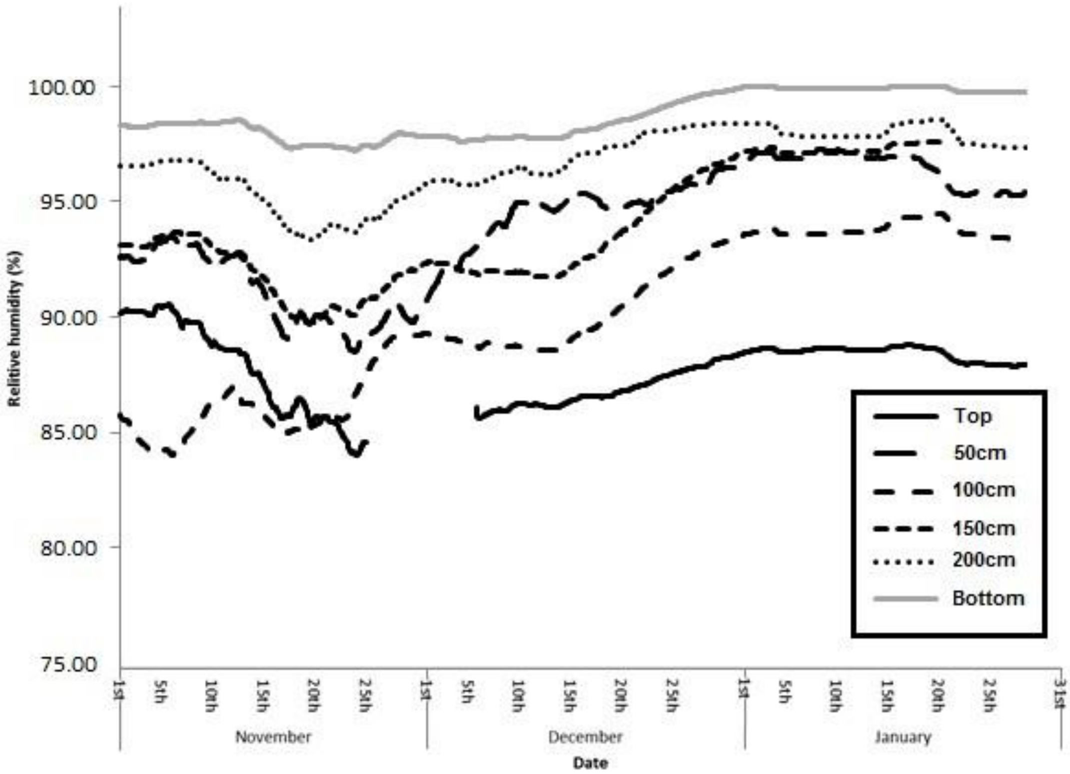
EW NS

Figure 4.47 Mean relative humidity taken from NS and EW grikes on the Holme Park Quarry site during the wet period.

In December of 2013, the Republic of Ireland received some severe winter storms which hit the West coast of the country. A movement in the polar jet stream placed Ireland in the path of several successive storm surges bringing strong winds, tidal surges and low pressure which caused flooding and extremely high tides. The storm caused excessive coastal flooding from winds which were the worst on record since 1839 (Met Éireann, 2017). Data from the Fanore site were sampled over this period in order to indicate the impact of storms on a coastal limestone pavement.

4.3.5.3.3 Relative humidity (Fanore)

NS



EW

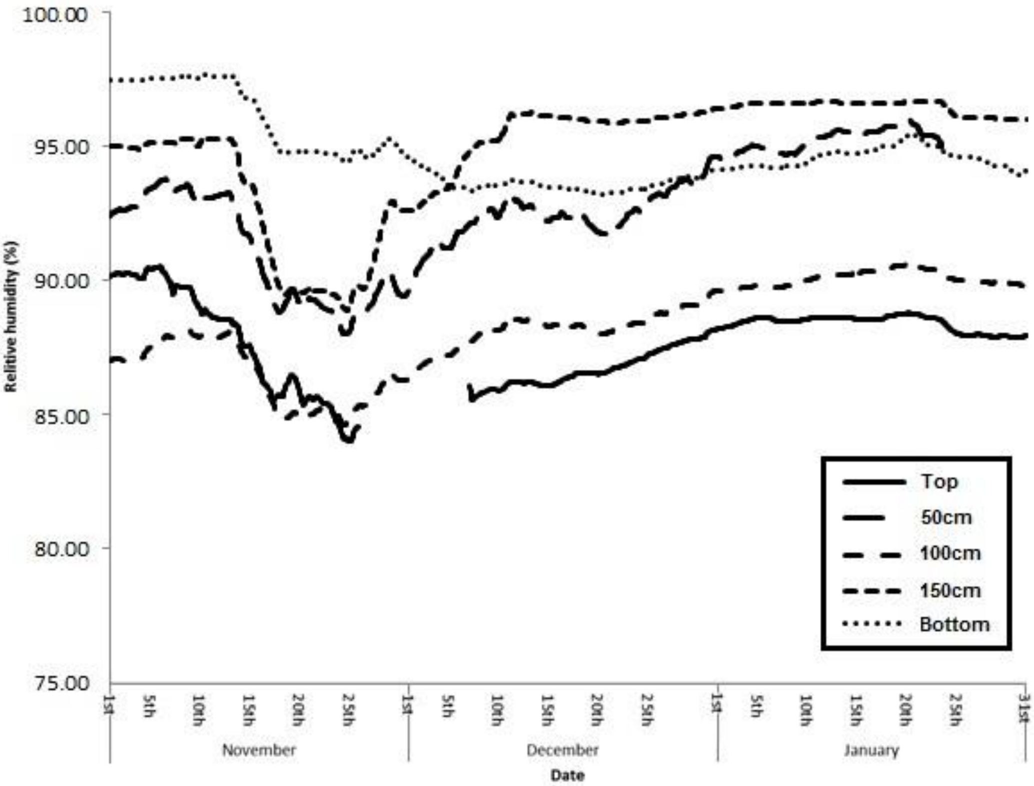
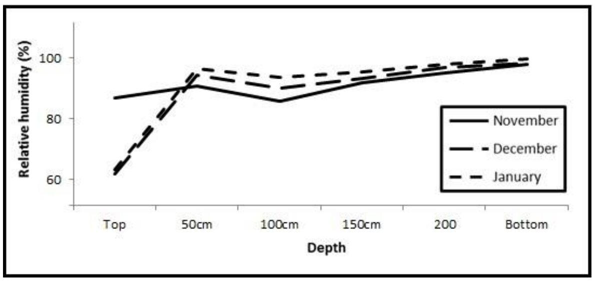


Figure 4.48 Relative humidity taken from NS and EW grikes on the Fanore site during the coastal storm period.

The Fanore grikes showed a decrease in the relative humidity in November before the major storm surge began. Relative humidity then began to increase as storms hit the Atlantic coast of Ireland over December and January. Relative humidity does not stay around the 100% mark as it does in Holme Park Quarry. It is unclear why this would be; however, possible hypotheses may involve the greater wind-speeds over Ireland during these storms (Met Éireann, 2017) compared to the flooding in the north of England (Met Office, 2017b).

NS



EW

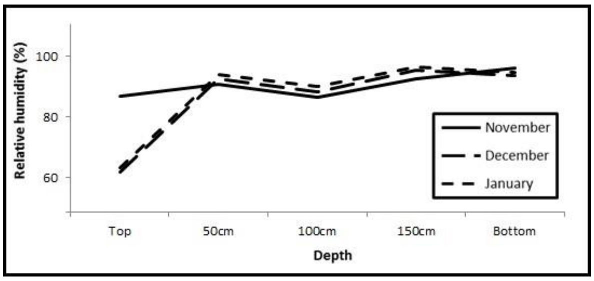


Figure 4.49 Mean relative humidity taken from NS and EW grikes on the Fanore site during the coastal storm period.

4.3.5.3.4 High precipitation implications

As reported, the temperature in both grikes of Holme Park Quarry experienced far higher temperatures than normal, and the relative humidity at all depths remained close to 100% for the whole month of December. In the Fanore grikes, the relative humidity increased as precipitation increased; however, the same extremes of relative humidity observed in Holme Park Quarry were not observed in Fanore. The invertebrates found in grikes tend to be adapted to conditions of high relative humidity (York, 2009). As such, precipitation on the scale seen in the natural experiment may not have a detrimental effect on the grike as a viable habitat for invertebrates. The limestone that makes up the superstructure of the pavement is also well suited to dealing with excessive rainwater. Naturally occurring flaws in the limestone provide channels for excess water to drain through so that any sudden downpour is short-lasting in effect (Ginés et al., 2009) and has minimal impact on the flora.

4.3.5.4 Subsection conclusions

By observing the interaction between the severe external weather and internal grike microclimate, it is possible to produce an idea of the way that the grike microclimate may react to more frequent severe weather in the future (Pachauri et al., 2014).

Severe cold and heat have indicated the extent to which the grike microclimate is cooled or heated by the thermally stable limestone surrounding it. While it is not possible to definitively state that the stability of the grike temperature is due to the thermal mass of the clint limestone, the evidence thus far and the physical properties of the limestone make this a serious possibility. The severe heat and high light intensity experienced by the grike during summer indicate that there is a connection between high light intensity and temperature. This theme is explored in greater detail earlier in this chapter, in Subsection 4.3.2, where season and grike orientation were explored in relation to grike temperature.

These incidental opportunities to observe severe weather events have indicated that the grike microclimate is changed less by short term weather events and more by longer-term climate change. While it may be beneficial for grike inhabitants to be mainly protected from storms, droughts and cold snaps on the surface, a longer-term climatic change like that predicted may be inescapable for even the most stable microclimates.

4.4 Conclusion

Conducting a long-term study of multiple limestone pavement grike microclimates produced an unrivalled data set with which to explore many of the current theories of grike microclimate and produced several new insights.

This study revisited several previous assertions concerning the grike microclimate and tested them using a more substantial data set.

4.4.1 Stability with depth

This study has thoroughly tested the stability of temperature, relative humidity and light intensity. Despite splitting the data by year, site, month, hour and orientation, there appears to have been no occasion during which the grike microclimate is less stable than that at the surface.

4.4.2 Changes to microclimate by the hour and month

Over 24 hours the microclimate of the grike was a more stable version of the surface, but over the year, more nuances were observed. The temperature inversion observed by Burek and Legg (1999) during autumn, has now been seen to occur in both autumn and spring such that the surface is warmer than the grike during the summer and the surface is cooler than the grike during the winter.

The diurnal and annual cycles within the grike have been observed to interact with both one another and with the depth of the grike such that the most stable temperatures are recorded from the deepest regions of the grike during the night in winter. These interactions are used in Chapter Six when creating a simulation of the temperature of the grike over a range of time scales and in a specific emissions scenario.

4.4.3 Orientation

Over the year, the EW grike was found by this study to be warmer on average. However, higher temperatures are reached in the NS grike during midday. In this study, light intensity was collected and shown to have similar patterns in variability and magnitude to temperature. Initially, these patterns were explored through simulations of the sun's movement, and then correlations between light intensity and temperature gave strong evidence that temperature change in the grike was due in part to insolation. The correlation between temperature and light intensity and the different amount of light entering NS and EW orientated grikes, may explain the difference in temperature in differently orientated grikes. This variation in microclimate between different orientations of grike presents a possible basis on which there could be considered to be varying geodiversity impacting biodiversity, within a single limestone pavement.

4.4.4 Variation in the microclimate with limestone pavement Group

Willis (2011) wrote in her PhD thesis that limestone pavements could be grouped into six distinct classifications based on a large number of criteria. In Willis's thesis, it is speculated whether a "closer examination of the limestone pavement microclimate and topography relating to each limestone pavement Group would provide valuable additional information for the future development of this holistic classification". In this study, three of the limestone pavement Groups used by Willis (2011) have been studied and were found to have very little difference in microclimate, apart from some similarities between the microclimates of High Folds and Dale Head. These similarities are thought to be based on overall grike depth.

The lack of difference in microclimate between pavement Group classifications could be for several reasons. The Groups selected in this study tended to favour grikes which are deeper and therefore share several characteristics in common, and this research indicates that even under the stress of severe weather events, the microclimate changes very little within the grike.

4.4.5 Temperature change is more rapid when increasing

The hourly frequency of the data collection has made it possible to observe how quickly the temperature changed over time. The greater frequency of data has increased the precision of attempts made to quantify the speed with which temperature increased and decreased. These observations have shown that in the grikes used, the temperature in the upper portion increased more rapidly than it decreased, over most of the year. Toward the lower portion of the grike, there was observed to be more equality in the rates of increase and decrease of temperature. At extremes of depth, there was, in fact, a more rapid decrease in temperature during some periods of the summer.

4.4.6 Time delay

The difference in the rate of temperature change at the surface and at different depths has led to the identification of further nuances in the grike microclimate. Using techniques which to the knowledge of the author, are new to the study of grike microclimate, it has been possible to quantify the time delay in temperature change over a year. The innovative techniques used indicated that during the summer, there was a far greater delay in temperature change between the surface and the base of the grike than there was during the winter.

4.4.7 Impact of severe weather

This study has taken place over an extended period. Extending the data collection period increased the probability of several severe weather events occurring in the grike locations. The reaction of the grike microclimate to severe cold, heat and precipitation were recorded and analysed. The high temperature in summer provided evidence to support the hypothesis that the limestone plays a role in stabilising the temperature of the grike due to the far greater thermal mass of limestone when compared to air. Observations of severe precipitation over a three-month period has shown that persistent rain resulted in increases in relative humidity. These increases may just increase the grike relative humidity as was found in Fanore or result in long periods of 100% relative humidity as was the case in Holme Park Quarry. This subsection illustrates that the grike may have a resistance against short term changes to weather but also may be vulnerable to longer-term climate changes.

4.4.8 Zonation within the grike

Distinct zones within the grike have been hypothesised as part of this investigation. The upper 75cm have been observed to have a greater rate of change in light intensity and temperature than lower zones. It is possible that the rapidly changing temperature in this zone is due to the limited reach of direct solar radiation, or may be due to the extent to which air in the grike mixes with that of the outside environment.

Although not distinctly zoned, the values for relative humidity recorded in the grike do decrease with depth and increase substantively in close proximity to the base of the grike. The increased relative humidity at the bottom of a grike presents the possibility of a variation on the microclimate given by depth, for particularly shallow grikes. The possibility of zones within a grike and the impact of the grike floor on the microclimate provide further arguments to propose that geodiversity can be found to affect microclimate, and possibly biodiversity within a single limestone pavement.

4.4.9 Limitations

The methodology used for this study provided a great deal of valuable data which provide several insights. There are, however, aspects which will need to be revised were this study to be repeated. The relative humidity data logging presented several issues which came to light during the study. Relative humidity within a grike remains at 100% for a vast majority of the time. The consistently high relative humidity presented a less nuanced picture of this aspect of the grike microclimate when compared to either temperature or light intensity. Although this measure was collected over the same period as the other measurements, relative humidity has shown very little variation with depth or difference between grikes of differing orientation. Personal communication from a data logger engineer (France. S, Linetop Ltd) suggested that it appears that the technology used in relative humidity loggers is not yet sophisticated enough to measure small fluctuations in relative humidity in environments close to saturation.

The weakness of relative humidity logging technology was particularly evident when the grike experienced periods of high relative humidity. Despite this shortfall, data were collected in order to draw limited conclusions. Were this study to be continued, it is recommended that a more sensitive method for relative humidity measurement should be used in order to identify any further nuances.

In Chapter Three, it is stated that, by using the chosen methodology to select pavements to study, geographical representation has not been possible. This has limited the confidence by which the conclusions of this study may be said to be characteristic of all limestone pavements.

4.4.10 Future study

4.4.10.1 Further studies into grike humidity

Subsection 4.3.1.3 details an increase in relative humidity at the bottom of the grikes, which is hypothesised to be due to the moist substrates found at the bottom of each grike. Further study could investigate this effect further by collecting relative humidity data from a range of similarly orientated grikes of different depths situated on the same site. In this way, it may be possible to quantify the effect that the grike base has on relative humidity. In order for such a study to be a success, there needs to be an advance in the technology available for monitoring relative humidity. For the reasons given in the limitations to this study, the current technology may be too temperamental to record relative humidity data for accurate modelling.

4.4.10.2 Continuation and extension of microclimate study

This study has provided the longest continuous study of grike microclimate known to the author. Continuation of this study as a way of monitoring the grike microclimate over the coming years would be valuable to land managers, by providing a record of how or if the microclimate changes in relation to the macroclimate. Further studies of the grike microclimate could usefully include sites from a wider range of macroclimatic conditions and limestone pavement groupings. This would improve the representativeness of microclimatic data and create the possibility for a broader range of conclusions.

In the methodology to this study it was identified that, by using Willis' (2011) grouping system for sites in the UK, the ability to represent sites was limited to those in the areas in which the Groups were established. Should future research expand Willis' methodology to sites in Republic of Ireland and other countries in the UK, it may be possible to select a wider range of sites for microclimatic study, on an expanded set of grouping criteria.

5. Foundational simulation of airflow in a grike

5.1 Introduction

5.1.1 Airflow in the grike

Air passage has been chosen as a parameter for investigation due to the impact that air from the external environment has on the more stable grike microclimate. The mixture of external and internal air affects the stability of the grike microclimate by driving temperature and relative humidity instability (Yarranton & Beasleigh, 1969). As well as impacting the microclimate, the movement of air also affects the ecosystem of the grike, as discussed in greater detail in Subsection 2.3.2.3 (Colebourn, 1974).

Multiple authors have observed that grike form varies greatly from one site to the next and even within a limestone pavement (Trudgill, 1985; Vincent,1995; Willis, 2011). The diversity of grike morphology from around the British Isles is exemplified in Figure 5.1. Such differences in shape depend upon lithologic factors such as join frequency and bedding thickness (Ford & Williams, 1989). Grikes form can also be influenced during the pavement formation. If the pavement is covered by soil, the transition from clint to grike (lip) is rounded or even tapered, especially when covered by peat. If soil erosion exposes the clints, the angles are sharper. More rounded forms of pavement have been found under peat cover (Zseni, Goldie & rá nyKevei, 2003). The slope can also influence pavement surface, resulting in three major forms. Rillenkarren is formed on steeper slopes and appears as narrow and closely packed channels separated by a sharpened crest. Trittkarren is formed on less steep slopes, which result in a variety of subforums sharing the property of smooth surfaces divided by small steps. Kamenitzas are formed on flat surfaces and appear as depressions in the clint known as “solution basins” (Trudgill, 1985).

Figure 5.1 Depiction of the diversity of limestone pavements from left to right; First Row, Scar Close (Yorkshire Dales, UK), Hutton Roof (Cumbria, UK), Crummack Dale (Yorkshire Dales, UK) and Cam High Road (Yorkshire Dales, UK). Second Row, High Farm Allotment (Yorkshire Dales, UK), Bryn Pydew (North Wales, UK). Third row two locations on the Fanore area (The Burren, Republic of Ireland).

5.1.2 Simulating grike airflow

Yarranton and Beasleigh (1969) hypothesise that vertical airflow is reduced as grikes become narrower, producing a greater degree of stability in narrower grikes. This phenomenon has been shown to occur in street canyons which mirror the shape of a grike. Here the width and height of street canyons influence the flow of air inside the gap between buildings. It has also been observed that the slope of roofs either side of a canyon can alter the flow of air passing between buildings (Kastner-Klein, Berkowicz & Britter, 2004) much like the shape of a grike lip may provide a similar influence within a grike. Interpretation of the effects of the grike's shape on the airflow within the grike borrows heavily from the field of street canyon research because of the structural similarities possessed by both arrangements. However, as previously mentioned in Subsection 2.2.5, an exact comparison cannot be made, and this topic is discussed in greater detail. This chapter details the second half of the research undertaken to complete Phase One of the methodological structure. This chapter aims to realise the fourth objective of this thesis through experimental manipulation of the form of the grike and the experimental conditions, in order to observe the importance of grike features such as depth, width and lip curve. In this way, this chapter meets the need for an investigation of the airflow in grikes which makes it possible to observe a qualitative indication of the air movement in and around the grike highlighted in the introduction to this thesis.

5.1.3 What is CFD?

In Chapter Three, it has been indicated that it was unfeasible to collect air passage data from each of the pavements studied as has been done for temperature, relative humidity and light intensity. This limitation was due to limits in accessibility and technology available. At the time of writing the University of Chester does not have access to wind tunnels which may be able to recreate the grike environment physically. In place of real-world measurement, Computational Fluid Dynamics (CFD) is used to simulate the air passage within a grike. The field of fluid dynamics seeks to simplify the complex patterns of gases and fluids in the physical environment, and CFD the computational branch of this study (Tritton, 2012; COMSOL Inc., 2014). In this instance, CFD is used to take the place of an experimental wind tunnel containing air of a constant speed, in which air flowing around grikes of differing shape and size can be observed.

The use of CFD is quickly becoming an industry standard for simulating and testing airflow in engineering (Kabošová, Kmeť & Katunský, 2019). As early as 1997, studies investigated the use of CFD alongside traditional wind tunnel experimentation (Alexander, Jenkins & Jones, 1997). CFD and wind tunnel usage have been compared by several other papers since this work (Fothergill, Roberts & Packwood, 2002; Stathopoulos, 2002; Huber et al., 2004; Toparlar et al., 2015). In certain cases, wind tunnel simulations are evaluated by comparison with CFD simulations, which are then used as the reference material (Blocken, Stathopoulos & Carmeliet, 2007). It is predicted that the use of CFD will continue to become more mainstream among the non-engineering community, and such users have been dubbed CFD guerrillas (Shengwei, 2014). This trend can be seen in the use of CFD in more environmental and geological studies. These range from simulating water flow rate to assess river suitability for migratory fish (Haro, Dudley & Chelminski, 2012), simulating airflow around leaves to find potential ecological niches for pests (Fatnassi et al.,2013) and simulating the flow of sand grains in a dune system (Wakes, Maegli, Dickinson & Hilton, 2010). Compared to the more regular conditions being simulated in engineering, natural systems have widely varying forms and properties making their simulation more ambitious and the need for foundational work is essential (Wakes, Maegli, Dickinson

& Hilton, 2010). Also, CFD is still a new technique for ecology, and there are several innovations required to make the software accessible for the majority of CFD guerrillas (Shengwei, 2014). Foundational studies are conducted with simplified or generic flow physics and geometry construction. These are used to obtain the basic insights into flow behaviour to isolate particular characteristics to study. In the field of CFD research, there is the expectation that more complex or applied studies will supersede foundational studies (Blocken, Carmeliet & Stathopoulos, 2007).

5.2 Methodology

5.2.1 Software

The simulation was conducted using the CFD module of COMSOL to simulate the compressible flow of air over the grike (COMSOL Inc., 2014). COMSOL is a general-purpose platform for simulating engineering applications. Commercial CFD codes used in COMSOL have the advantage that they are widely used and trusted in the industry; however, some aspects are generalised, introducing inaccuracies into specific applications (Balogh, 2012). So as not to introduce inaccuracies into the simulation, complex parameters such as roughness were not used in this foundational study of grike airflow.

In order to standardise the modifications, a standard limestone pavement template was created using COMSOL's inbuilt geometry software, and modifications are applied to this.

In order to accurately simulate the grikes found on limestone pavements, it is important to understand the formational properties of limestone pavements as a whole.

5.2.2 Grikes

As a foundational study of grike flow physics, the geometries used were simplified but grounded in the realities of grikes observed on limestone pavements. In the simulation of grike air currents, the walls of the grike were regular and smooth whereas in reality grike walls are pitted, uneven and often slanting (Vincent, 1995). When creating a physical simulate, there is a compromise between realism and idealism. As a simulation becomes more realistic for a specific scenario, the generality of its use becomes compromised (Savory, Perret & Rivet, 2013). Smooth walls and regular dimensions were used in this foundational simulation so as not to introduce complexities which may obscure the general flow being represented. Further discussions of this limitation are found in Subsection 5.4.3.

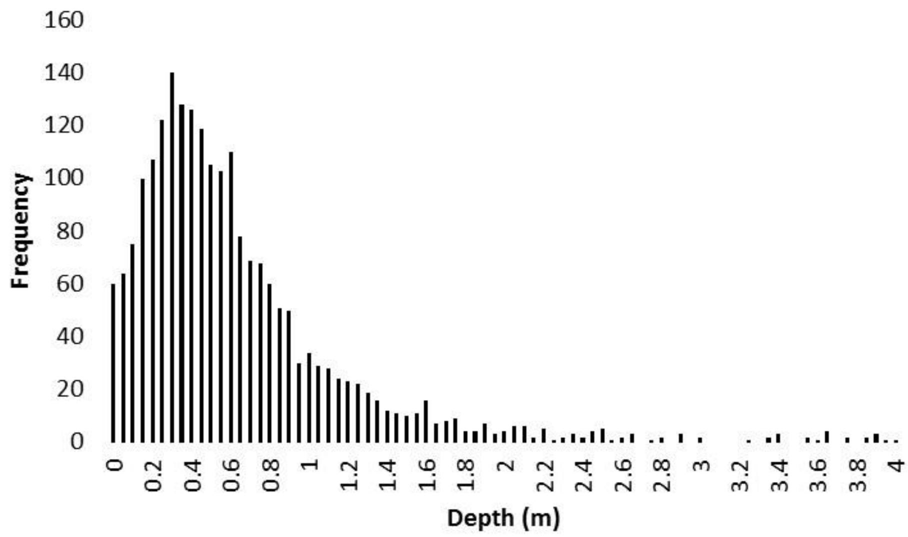
As has been mentioned earlier in this study, grikes can be defined in several ways. The most pertinent to this study is that used in the previous chapter "A vertical fissure, formed by the solutional widening of joints, which regularly divide an exposed limestone surface into sections or clints". Clints can be defined as “flat-topped rock outcrops …, separated by widened joints or cracks” (Sweeting et al., 1965; York, 2009) however as can be seen from the introduction to this chapter; this simple definition is not characteristic of all grikes or clints. The width and depth measurements were taken from both Willis’s (2011) survey of limestone pavements of Great Britain and a similar dissertation repeating Willis’s methodology in Ireland (Higgins, 2014), to make this simulation representative of the grikes present in Great Britain and Ireland. These two studies, in combination with measurements made as part of this study, have been used to create Figure 5.2 that shows histograms of grike depth and width.

5.2.3 Grike features

There is a balance between overfitting and over-generalisation when simulation an environment (Zuur, Ieno & Smith, 2007). This balance is particularly important to consider when selecting the features to use when simulating the airflow within a grike (Versteeg & Malalasekera, 2007). For this reason, only grike width, depth and lip shape were considered. These features are common to all grikes and have a precedent for influencing the airflow in grikes or street canyons (Kastner-Klein, Berkowicz & Britter, 2004; Simoëns, Ayrault & Wallace, 2007; Willis, 2011).

<u>5.2.3.1 Depth</u>

The simulated grike depths used and the frequency of samples were based on the measured distribution of grikes in limestone pavements. Using Figure 5.2, it can be seen that the data has a truncated normal distribution with a mean grike depth of 0.6 m. Based on an assumption of normality, depths which fall within one standard deviation (0.21m, which are rounded up to 0.22m) were sampled at intervals of 0.02m, and depths falling outside one standard deviation were sampled at a frequency of 0.05m. This sampling frequency meant that there was more precise simulation between the depths of 0.08 m and 0.52 m. Outside of these values, sampling was taken with less frequency until the maximum recorded depth from this study (4m) was reached.



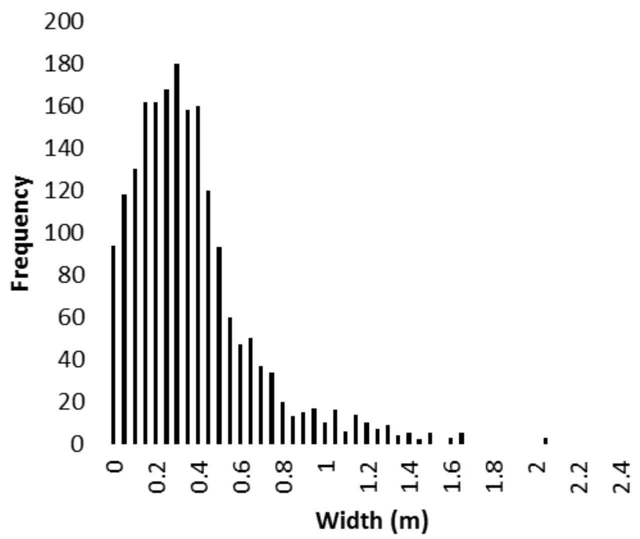


Figure 5.2 Histograms showing the depths (top) and widths (bottom) of grikes recorded in prior studies.

5.2.3.2 Width

The practice of rationalising sample frequency was not repeated for grike width due to the smaller number of values being used. The grike width has been sampled every 0.02m from 0.02m to 2m.

5.2.3.3 Grike lip curve

The grikes in Figure 5.1 illustrate the variety of grike lip forms present on limestone pavements. The image of Scar Close in Figure 5.1 illustrates a grike lip with a typical 90° sharp angle, as illustrated in Figure 5.3. This standard grike can be modified in certain ways. For example, the grike in Hutton Roof in Figure 5.1 has an exaggerated curve from clint to grike. The magnitude of this curve can be quantified as x, which is the radius of the truncated circle used to create the curve. The magnitude of this curve is often linked to the amount of weathering experienced by the grike before its emergence from glacial drift (Jones, 1965; Zseni, Goldie & rá ny-Kevei, 2003), for this reason, the value of x can vary between grikes and pavements. In order to measure the effect of x the testable values started at a minimum of 0 (Figure 5.3 a) and were sampled with a frequency of 0.01m until a maximum of 0.3m was reached. The value of 0.3m was chosen from the observation of limestone pavements and measuring the maximum curve.

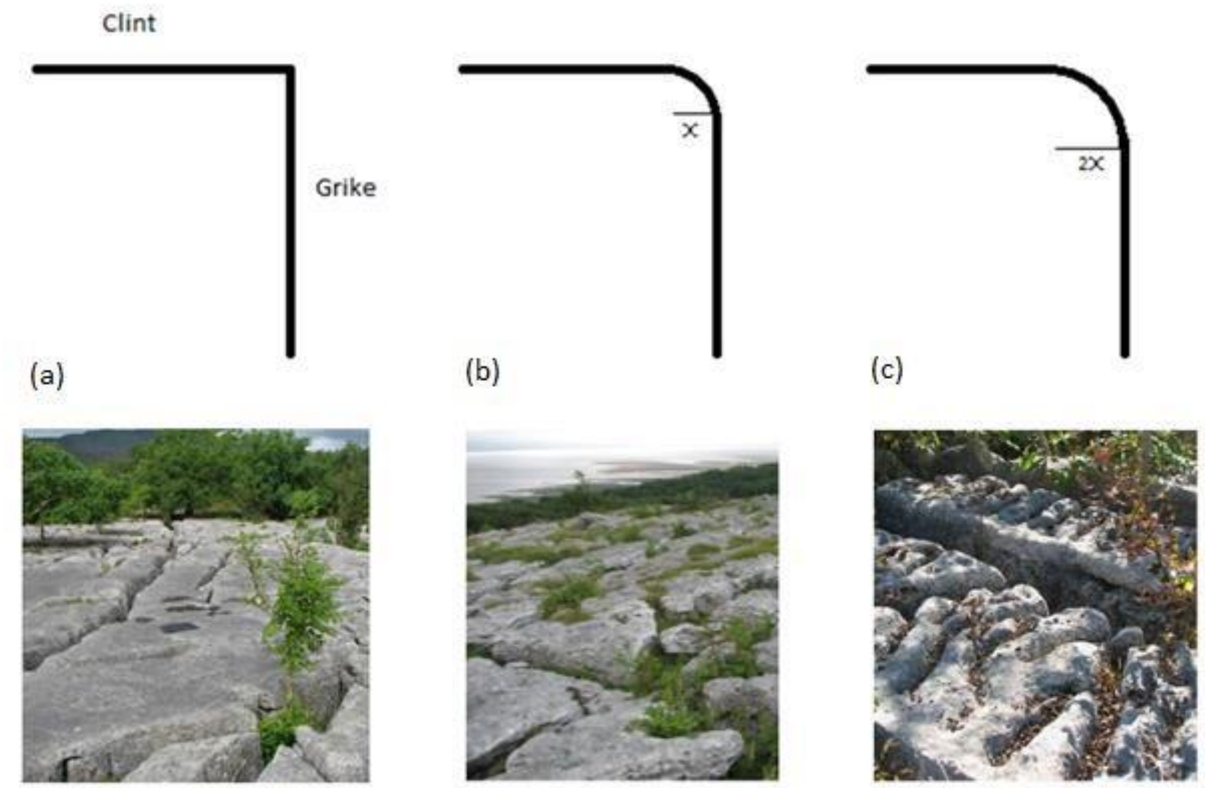


Figure 5.3 Increasing curvature of grike lip form from (a) curve = 0 to (c) curve = 2x.

From left to right Scar Close (Yorkshire Dales, UK), High Farm Allotment (Yorkshire Dales, UK), Hutton Roof (Cumbria, UK)

5.2.3.4 Orientation

Orientation has been theorised to influence the microclimate of grikes through the effect of the sun from different aspects (Yarranton & Beasleigh, 1968; Goldie & Cox, 2000; Alexander, Burek & Gibbs, 2007) and Silvertown (1982) postulated that seasonal differences in microclimate might relate to the orientation of grikes, and as yet no data set has been able to establish this conclusively. It has been mentioned earlier in this study that the orientation of forms such as street canyons can have an effect on the air movement due to convection flows and the direction of the wind over the top of the grike can also affect its behaviour inside the grike (Ali-Toudert & Mayer, 2006). The effect of street canyon orientation on airflow was exemplified in the investigation undertaken by Kumar, Fennell & Britter

(2008) which has shown that the wind flowing over a canyon perpendicular to the wind direction formed stronger eddies and disturbance, whereas if the canyon and wind followed the same direction, there was little turbulence (Belcher, 2005).

Due to the effect that different orientations can have on air passage, it was decided to standardise the orientation of the grike. The 2-dimensional grike simulations have been conducted where the grike is positioned at 90° to the flow of air.

5.2.4 Simulation constants

A non-linear stationary solver based upon the PARDISO solver was used to compute the airflow within a grike because this problem is considered to be "static or steady-state". Using a static solver means that the solution does not develop over time, nor are there moving parts which require observation over multiple time steps. A stationary solver runs a simulation until "convergence" when a simulation is resolved to a specified tolerance (Versteeg & Malalasekera, 2007). The optimisation solver used by this study is the Nelder-Mead Simplex Method which resolves when the difference in successive values of the objective function is 0.001 (relative tolerance = 0.001) (COMSOL Inc., 2014)

5.2.4.1 Dimensions of the top space

The top space (the area of air above the grike) was an empty top box of dimensions 2m wide by 1m deep. Alongside the wall physics, this mimicked an infinite space above the grike so as not to interfere with the grike being simulated.

5.2.4.2 Walls

Each of the walls provided a different function in order to simulate an environment as close to reality as possible.

- The left wall generated an input of air at a steady velocity in a laminar flow.
- The top wall provided a constant moving wall away from the input wall, creating what is termed a "lid-driven flow". This was done to simulate the physics of a constant infinite body of air moving at a constant speed (De La Fuente, Causon, Ingram, Mingham & Raper, 2003).
- The right wall was an open wall with no other physical properties.
- All further walls were solid non-permeable walls without texture. The bottom wall and walls representing the grike were ridged and smooth.

This simplified scenario was based on reality but modified in order to test only the properties being manipulated in this study

5.2.4.3 Grid properties

The grid system created within the computational domain used a free, unstructured triangular mesh containing cells ranging in size from $2.25*10^{-4}$m to 0.0525m, with a corner refinement factor of 0.25.

5.2.4.4 Source gas

Source gas was air using COMSOL's present physical properties (COMSOL Inc., 2014)

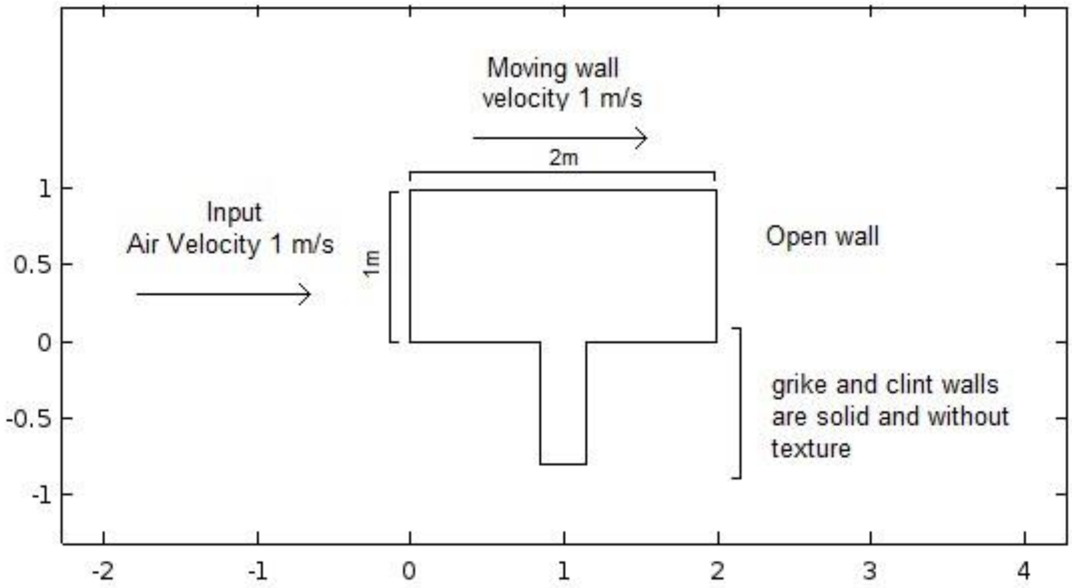


Figure 5.4 Illustration of the simulation parameters.

5.2.4.5 Airspeed and flow properties

Laminar flow was selected for this simulation because of the lower Reynolds' number (Re) involved in the simulation. The laminar flow of air in the grike was governed by the compressible flow formulation of the Navier-Stokes equations. In order to maintain a laminar flow to provide descriptive simulations of airflow in a grike, a low Re was required. The Re is derived from properties of a fluid or gas and the flow velocity. If the Re of the air simulated becomes too high the laminar flow becomes turbulent (Re > 4000), and it may also be possible that the simulation does not resolve to a stable state (Bansal, 2005). The Re represented in this simulation provides the controlled conditions to be able to observe the underlying physics of the air transported through the grike (Simoëns, Ayrault & Wallace, 2007) and ensure that the turbulence observed was determined only by the characteristics of the flow inside the grike (Pavageau & Schatzmann, 1999).

In order to ensure simulations had a low Re airspeed was kept constant and laminar at U = 1 ms^{-1}, this wind velocity is described as light air (Strangeways, 2003). This air velocity and laminar flow were chosen to provide the most visibly descriptive diagrams possible. A lower air velocity would result in almost no air movement at all and take more iteration to reach a convergent simulation.

5.2.5 Analysis

The descriptive plots were used to show the air velocity within the grikes of varying depth, width and grike lip curvature. For ease of description, in all plots of the air velocity in a grike, the following remained constant:

- The flow of air originated and exits only from above 0 on the y-axis
- The flow of air originated from the left of the diagram and flowed toward the right side.
- The wall of the grike on the airflow origin side (left) was referred to as side A
- The wall of the grike on the airflow exit side (right) was referred to as side B

Line plots were used to illustrate the air velocity within the baseline grike and the grike with depth over 2m.

5.3 Results

Several different variations on the form of a Limestone pavement grike were selected, and the variation in airflow was tested using the COMSOL software.

5.3.1 Baseline

In order to account for the influences of different parameters, it was first necessary to describe the air passage over a grike of the average proportions, from now on referred to as the “standard grike”. The depth and width of this grike were gathered from the mean values of all grikes sampled during Willis (2011) and Higgins (2014) fieldwork. The grike of width 0.3 m and 0.6 m deep produced the flow featured in Figure 5.5.

The standard grike showed turbulent fast-moving air concentrated at the grike opening only where the grike meets the external environment. At the immediate mouth of the grike, there was greater air movement toward side B than side A. From this point down, there was a drastic decrease in airflow speed. The air movement observed in the grike body was directed vertically downward next to side B, and upward next to side A. These two contrary flows formed a larger circular motion of air reaching from close to the surface to 0.5m. At the base of the grike, there was a secondary air circulation that was extremely weak so as to be almost invisible in Figure 5.5. The flow of air on side A of the grike was around three times smaller than that on side B.

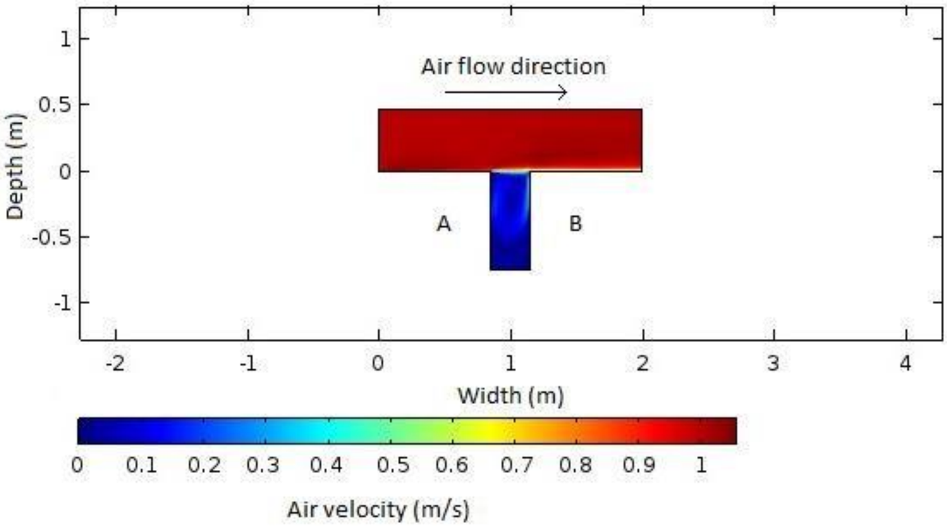


Figure 5.5 Air velocity diagram of the standard grike.

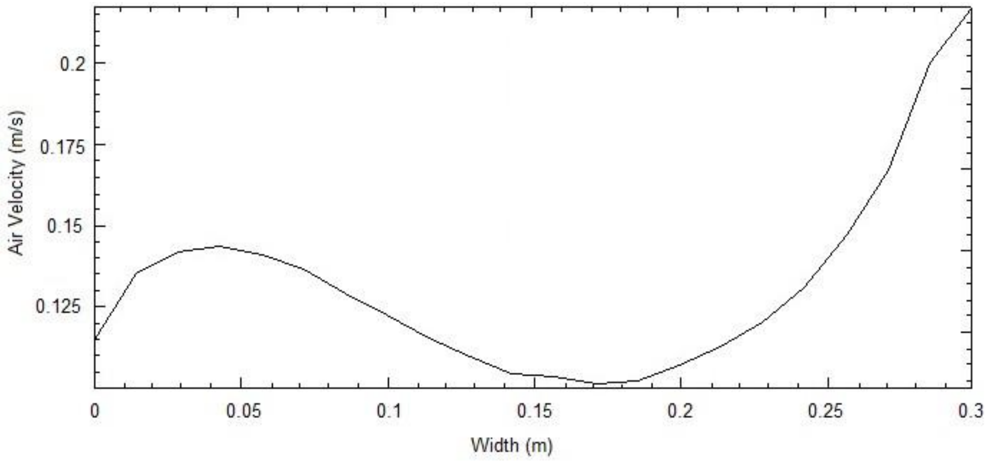


Figure 5.6 Mean velocity of the air taken from within the standard grike.

5.3.2 Depth

In the extremely shallow grike depth of 0.1m (Figure 5.7 a) the airflow differed from the baseline grike in several ways. There was a single defined circular flow of air on side B of the grike. Here the downward flow of air moved down side B and halfway along the base of the grike. Once the flow was halfway between sides A and B, the flow pitched upward. The airflow at the surface was very similar to that of the standard grike but horizontally elongated.

As the depth increased to 0.2m (Figure 5.7 b), the circulation of air within the grike extended downward. As the size of the vortex increased downward, it also extended laterally toward side A. The path of the air was then channelled vertically down side B along the base of the grike and passed the point on the base midway between the walls and then began to rise. When the depth and width of the grike were equal at 0.3m (Figure 5.7 c) the circulation of air in the grike had a roughly equal radius. It was notable that as the depth of the grike increased, the velocity of the air being circulated in the grike decreased. When the depth of the grike was 0.5m (Figure 5.7 d) deep, the velocity of air moving vertically along the walls had become greater than that moving horizontally along the grike floor. As depths simulated exceed that of the standard grike (Figure 5.7 e & f) there was little further change in the pattern of airflow within the first 0.5m. At the surface of the grike, the airflow was similar to that of the standard grike. The airflow was rapid over the surface of the grike and had a small incursion into the grike biased to side B. Below the surface there was a decrease in airspeed when compared to the surface as the first vortex was formed in the first 0.5 m of the grike. This flow of air moved more rapidly and in a smaller area when moving vertically along the walls than it did horizontally through the grike body, and the speed of the air was marginally faster toward side B than side A. Below 0.5m, there was evidence of a second weak circular flow of air extending to the bottom of the grike.

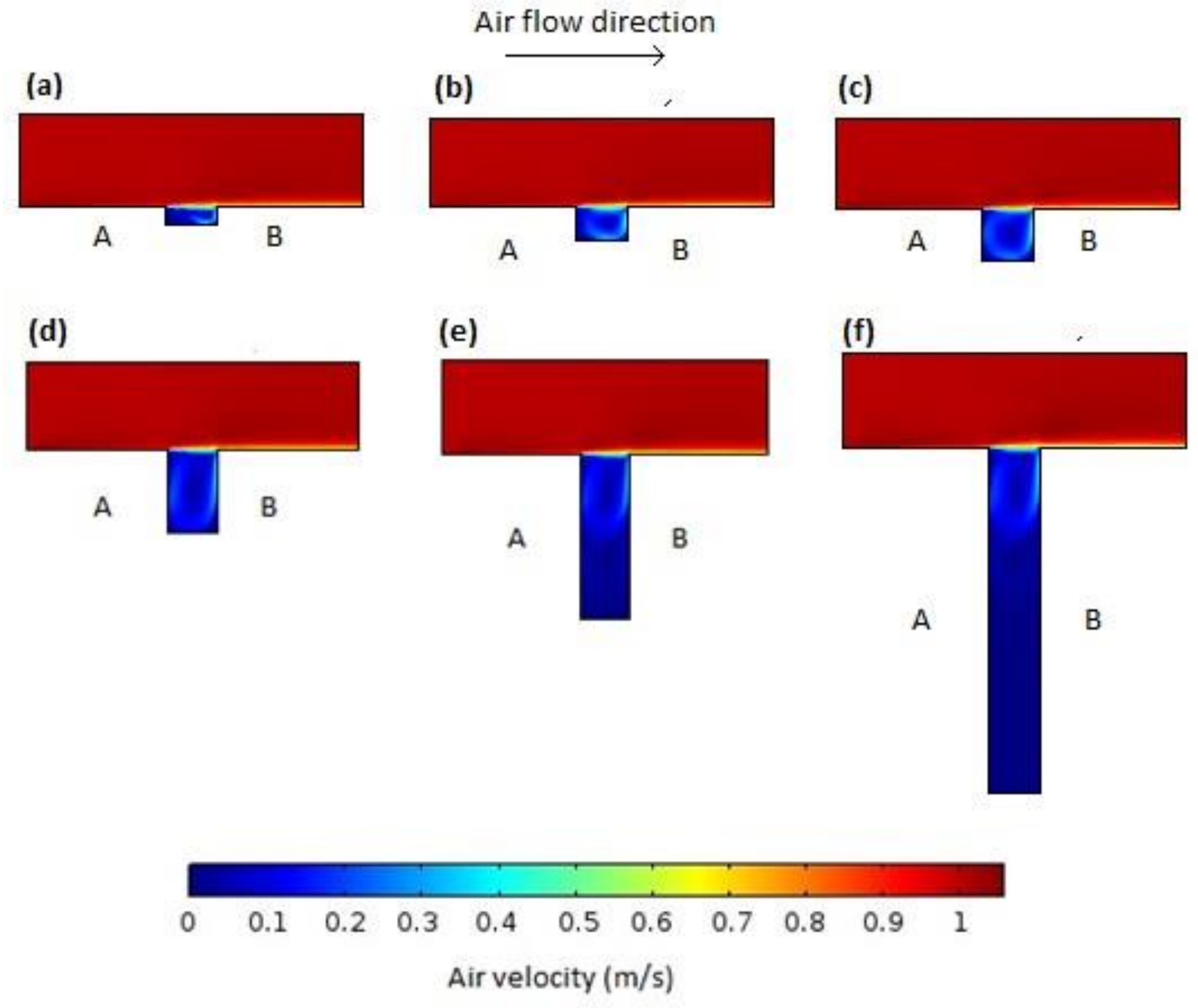


Figure 5.7 Anthology diagram of air velocity of grikes (depth = 0.1m to 2m, width = 0.3m).

(a)	depth = 0.1m	(d)	depth = 0.5m
(b)	depth = 0.2m	(e)	depth = 1m
(c)	depth = 0.3m	(f)	depth = 2m

Observation of airflow in deep grikes like that in Figure 5.7 f of a 2m deep grike show again that the surface flow was similar to that of the standard grike, and remained unchanged in grikes of the exceptional depth of 4m (Figure 5.8).

In each grike exceeding 0.5m in depth, it was observed that there was a weak circular flow below that of the primary flow at the surface. Figure 5.8 illustrates the weak yet tangible force of this circular flow, and that it was strongest on side A.

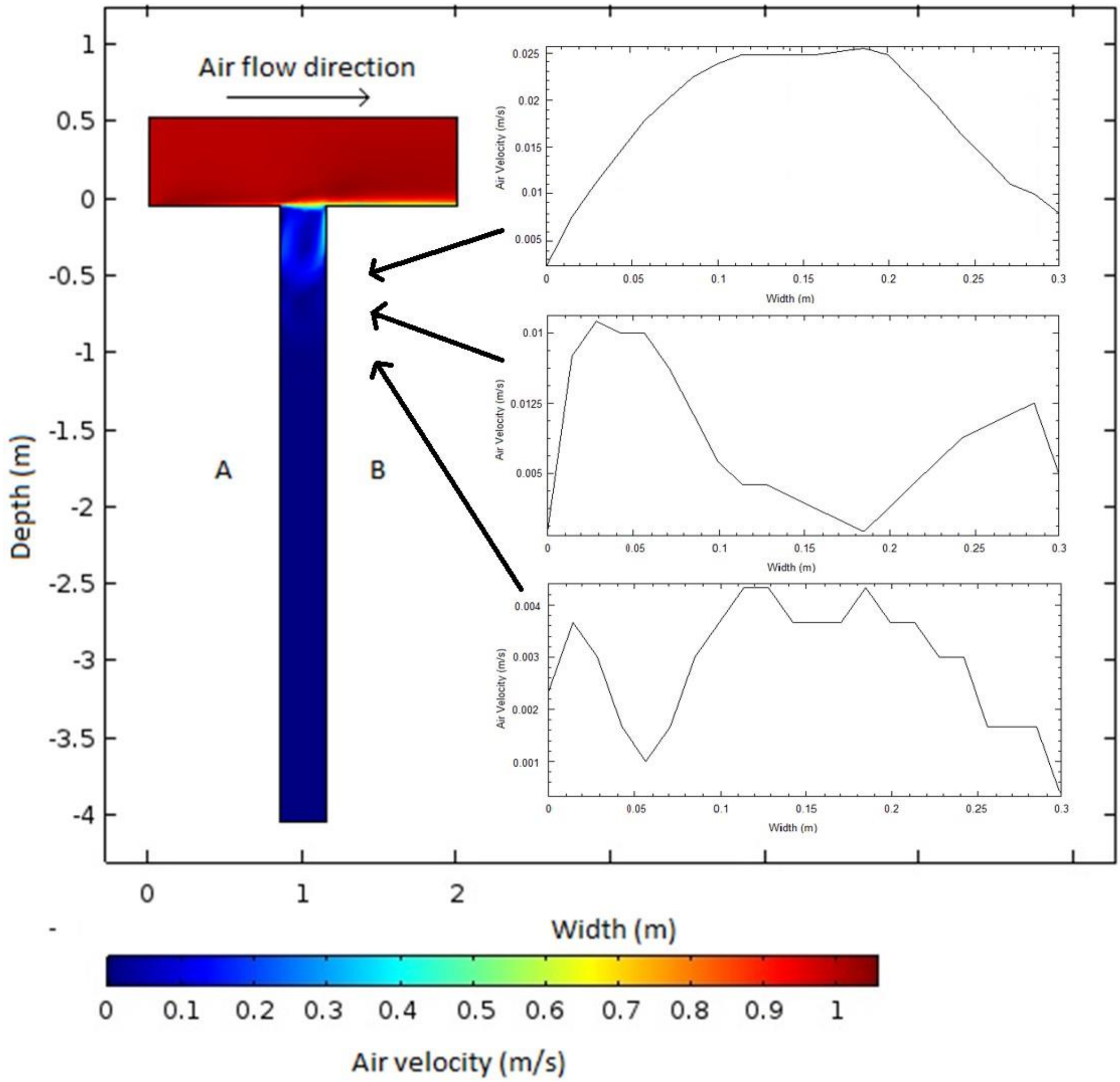


Figure 5.8 Air velocity diagram of grike (depth = 4m, width = 0.3m) illustrating air velocity at depth -0.5m, -0.75m and -1m.

5.3.3 Width

Figure 5.9 shows how the flow of air and the surface vortex evolved as the width of the grike increased incrementally. The narrowest grike simulated was 0.04m (Figure 5.9 a). The flow of air was slightly quicker very close to the grike mouth. Apart from this movement, the rest of the air in the grike was extremely still. The first width of grike to exhibit an air circulation was 0.12m (Figure 5.9 b). When compared to the standard grike, this extremely narrow grike exhibited some similarities and some differences. The airspeed at the surface was rapid and flowed faster toward side B. Below this point there was a circular airflow extending from the surface to 0.1 m with a centre offset toward side B. Below 0.1m there was very little air movement.

As the width of the grike increased the circulation of air near the surface became more established and extended downward. At a width of 0.2m (Figure 5.9 c) the air circulation reached the bottom of the grike, and at 0.44 m (Figure 5.9 d) the air movement interacted with the base of the grike. As the width of the grike increased further, the flow of air began to create a more rapid air movement at the base of the grike similar to that on the walls. This progression continued until a circular flow was created when both width and depth were equal.

When both depth and width were equal the circular flow of air was most rapid on the walls and base of the grike, however, at a width of 0.68m (Figure 5.9 e) the flow from side A joined the flow at the surface and began to form a complete circle. There was however a channel of slower air at the upper corner of side B where it met the surface. It can be noted that the circulation of air in the grike then provided an influence on the air outside the grike. The influence on the flow of air outside the grike was exhibited as an area of slower moving air extending above the grike that was more prominent toward side B.

At a width of 0.84m (Figure 5.9 f) the circulation of air within the grike became horizontally elongated while all other features remained the same. When the grike width reached 0.88m (Figure 5.9 g) the air circulation could no longer extend any further and became detached from side A. In the gap between the flow and the wall, the air was extremely still. This gap between the circulating air and side A was fully established when the grike was 1m wide (Figure 5.9 h), it was also notable that there was a channel of faster-moving air immediately next to side A. At a width of 1.2m (Figure 5.9 i) the width of the grike was twice that of the depth. The influence of the air exiting the grike was at his point, having an increased impact on the airflow almost 0.1m over the top of the grike. Most of the circulating air was constrained to the half of the grike closest to side B. On the half of the grike closest to side A there was a small amount of chaotic airflow close to the surface. In the body of the grike, there remained an area of slow-moving air close to side A and close to the vortex.

An extremely wide grike of 2m (Figure 5.9 j) in width could be considered to be a gap between limestone pavements as many do not have the characteristic flora associated with a grike (Thom, 2003). The simulation of the airflow, however, displayed that toward side B the circulation of air found in this grike was almost indistinguishable from that found in narrower grikes. Toward side A the air was chaotic in the upper half of the grike but retained some characteristic flows of air closer to the base of the grike. The air above the grike was greatly disturbed to a height of over 0.2m.

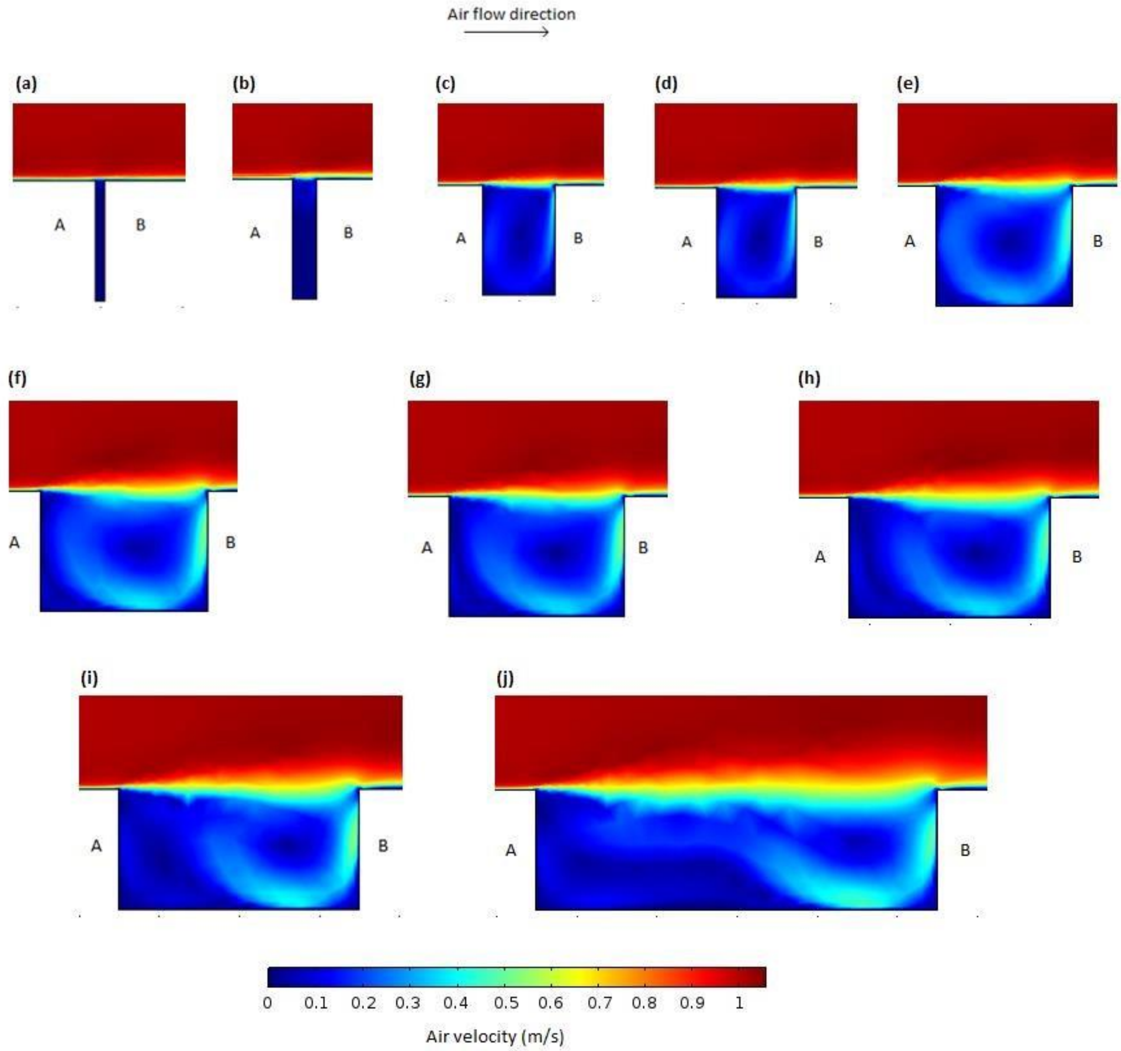


Figure 5.9 Anthology diagram of air velocity of grikes (depth = 0.6, width = 0.04m – 2m).

(a)	width = 0.04m	(e)	width = 0.68m	(i)	width = 1.2m
(b)	width = 0.12m	(f)	width = 0.84m	(j)	width = 2m
(c)	width = 0.4m	(g)	width = 0.88m		
(d)	width = 0.44m	(h)	width = 1m		

5.3.4 Grike Lip

In Figure 5.10, snapshots have been taken to show a range of grike lip curves with increasing radii, starting with Figure 5.10 a with a grike lip curve radius of 0.05m, and increasing in 0.05m increments until Figure 5.10 f which shows a grike with a lip curve of 0.3m.

In the first instance, Figure 5.10 a shows a grike with a lip curve of radius 0.05. In this simulation, the flow of air was almost indistinguishable from the standard grike. There was a vertically elongated circulation of air flowing down side B and up side A.

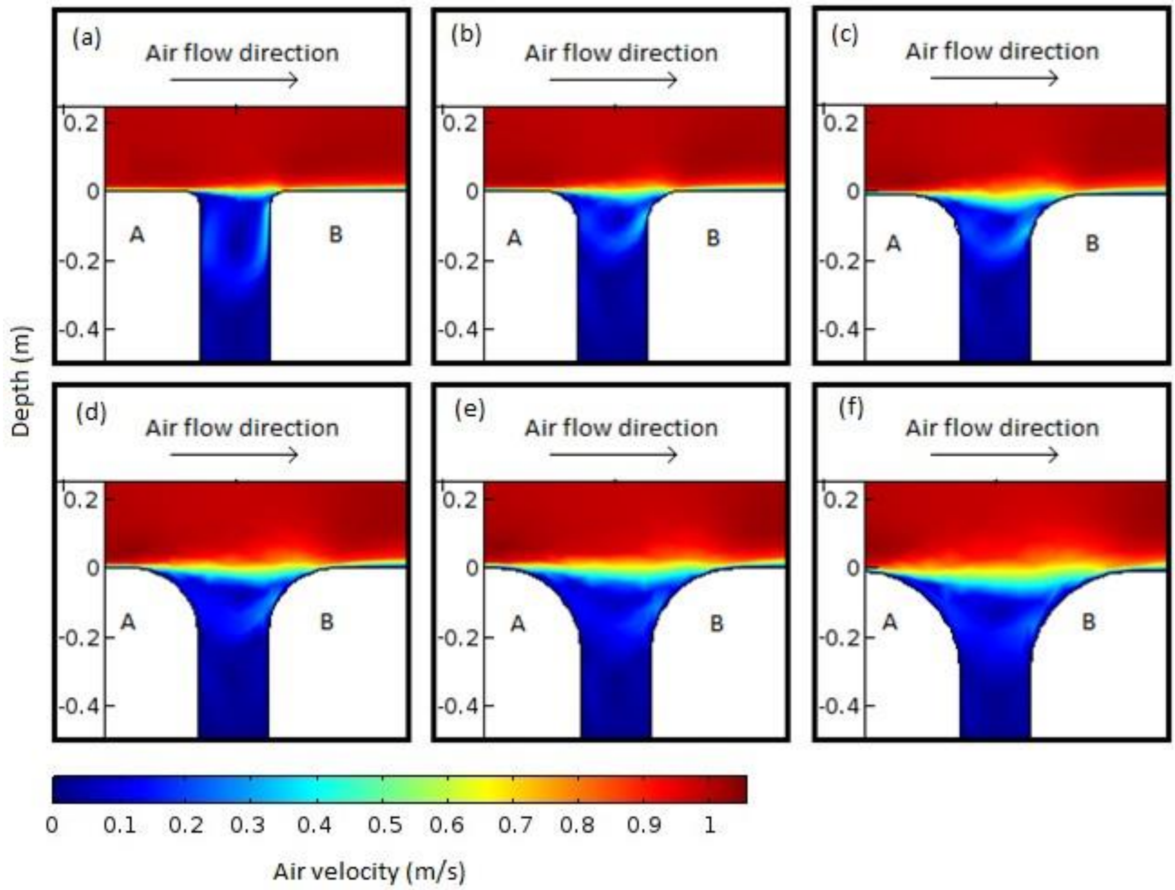


Figure 5.10 Anthology air velocity diagram of grikes (depth = 0.8, width = 0.3).

(a)	Lip curve radius = 0.05m	(d) Lip curve radius = 0.2m
(b)	Lip curve radius = 0.1m	(e) Lip curve radius = 0.25m
(c)	Lip curve radius = 0.15m	(f) Lip curve radius = 0.3m

By increasing the radius of the lip curve by 0.05m to 0.1m, there was an evident change in the shape of the air which circulated in the grike. In Figure 5.10 b, it can be seen that the flow of air was no longer vertically elongated, and consequently, the depth to which the circulation reached was diminished. In Figure 5.10 c, where the lip curve radius had increased to 0.15m, there was a greater influence of the air in the grike on the air flowing over the surface. As the curve of the lip increased through Figure 5.10 d to f the flow of air lost its distinct circular form and became more nebulous though not destroyed. The flow at the surface became more chaotic as lip curve radius increased, and there was also a further influence of the grike on the air flowing above the grike mouth. These results show that while there may be a typical form of airflow exemplified by the standard grike, there are also several other mutations of this flow caused by several changes in grike form.

5.4 Discussion

Thus far, the inner grike microclimate has been observed to be more stable than the macroclimate experienced above the grike. The stability of air within grikes was also found in comparable experiments of furrow depth in ploughed fields, which are described as having varying degrees of stability when compared to the external climate (Graser, Verma & Rosenberg, 1987). Structures such as grikes and furrows present an area protected by a windbreak formed from clints and plough ridges respectively. Windbreaks such as these are extensively used in ecological management to slow the passage of wind and provide protection to delicate species (Jørgensen, 2009).
Oke (1988) described several flow regimes for street canyons that may be applied to grikes (Figure 5.11).

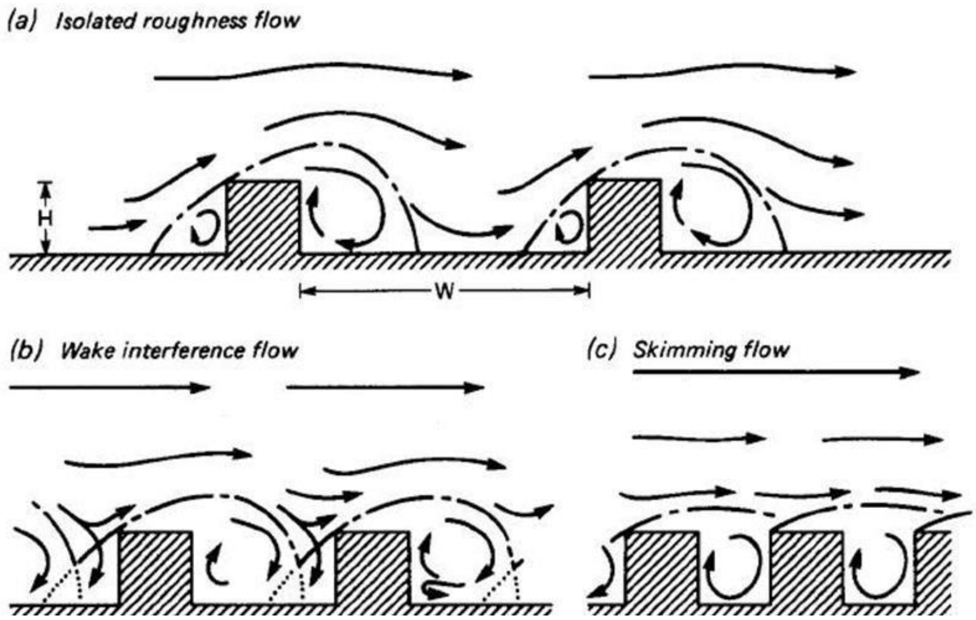


Figure 5.11 The Flow regimes associated with airflow over building arrays of decreasing W/H (Oke, 1988).

This subsection will discuss the shape of grikes in terms of the width to height ratio (W/H). This term is used widely in the urban street canyon literature to describe the aspect ratio of the canyon and might be repurposed to discuss the height and width of a grike as viewed from the grike base.

5.4.1 Types of Flow

The results of this study have indicated that the greatest stability is achieved when the grike is relatively deep compared to the width and has been the feature of the majority of the CFD simulations. This type of grike has a low W/H. In urban landscapes, street canyons with a low W/H of 0.6 (Oke, 1988) are considered to have a skimming flow regime (Figure 5.11).

Skimming flow (Figure 5.11 c) was introduced to the literature of street canyon flow dynamics by Oke (1988) when the three regimes of flow were described in Figure 5.11. Skimming flow in a grike simulation was characterised by the vortex which was formed and maintained by the air skimming over the surface of the grike. There was also a downward transfer of momentum from surface flow to downward flow into the grike on side B (Fernando, 2012). The centre of the vortex in a skimming flow regime is positioned slightly closer to side B, as observed in the results of this study. In a skimming regime, the downward motion of air on side B is greater than the upward motion on side A, this was observed in the simulation and is illustrated in Figure 5.6 of the results.

5.4.2 Flow in a grike

Within the grike mouth, a skimming flow developed that is analogous to that of a street canyon (Louka, Belcher & Harrison, 1998).

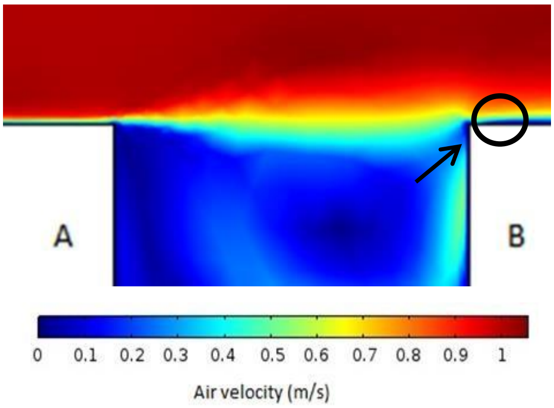


Figure 5.12 Exemplified surface flow to illustrate peak flow in the surface of the grike (circle) and escaping air from the vortex (arrow).

In the grike mouth wind velocity gradually increased with distance from side A until a point very close to side B was reached where flow rate peaked. After the peak flow rate, airspeed rapidly decreased until the edge of side B was reached (circled in Figure 5.12). Baik and Kim (2002) describe this exact process occurring over multiple metres when discussing the flow between two buildings.

However, this process was confined to cm in the grike.

In a street canyon, there was an updraft close to side B where air from the vortex could escape (arrow in Figure 5.12) (Hoydysh & Dabberdt, 1988). The updraft described by Hoydysh and Dabberdt (1988) was possible to view with tracer measurements unavailable to the simulations produced in this study and could provide a possibility for future research.

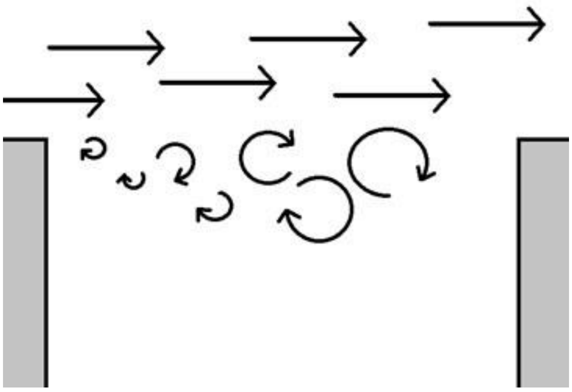


Figure 5.13 Illustration of turbulent entrainment within a grike.

The skimming flow in the grike was created by the movement of surface air over the mouth of the grike. The air passing over the grike created the characteristic vortex of a skimming flow through three processes. In the first instance, air entered the grike by turbulent entrainment (Figure 5.13) (Soulhac, Perkins & Salizzoni, 2008). This is a process by which air moves across a boundary; in this case, the boundary was that of moving air on the surface and stationary air in the grike (Tritton, 2012).

Once the air entered the grike, the moving air was resisted by drag on grike walls and flow separation occured (Soulhac, Perkins & Salizzoni, 2008). Flow separation is the process by which a flow adjacent to a wall becomes detached and turns into the interior of the grike due to a decrease in pressure (Wu, Ma & Zhou, 2007). In this instance, the change in pressure was due to the incidence of the grike and the flow of air departing from the clint surface.

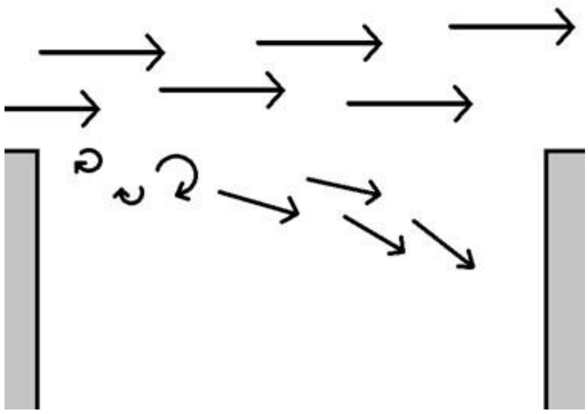


Figure 5.14 Exemplified flow separation.

Finally, if the grike was narrow enough to establish skimming flow, the bulk of the surface flow did not enter the grike, and a stable vortex was established by the flow of air skimming over the grike mouth (Baik & Kim, 2002).

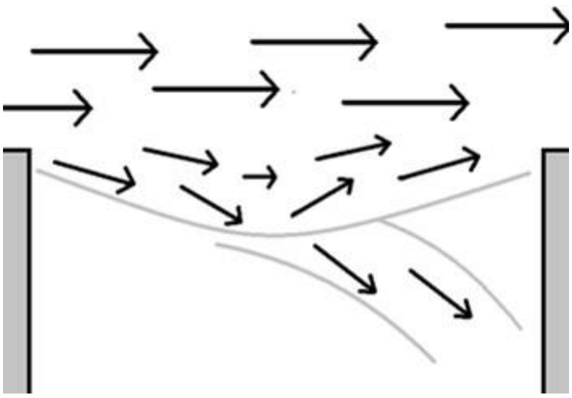


Figure 5.15 Exemplified surface flow.

This vortex is considered to be a rotational or forced vortex due to the required surface flow. Airflow from the surface provides the required impetus to continue the vortex, and without this flow, the vortex is not perpetuated (Majumdar, 2011).

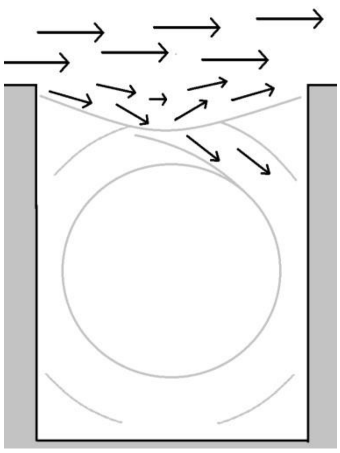


Figure 5.16 Exemplified forced vortex.

5.4.2.1 The lower limits of skimming flow in the grike

The results show that vortices appeared in the simulated grike only when a grike was at least 0.2m deep and 0.06m wide (W/H=0.3). In pipe flows, the diameter of a pipe increases the Re and therefore the chance of turbulence (Kaminski & Jensen, 2005). In a pipe, turbulence can affect the way a fluid behaves and may result in turbulence and eddies not observed in laminar flow (Lautrup, 2004). It may be that at the limits expressed in this study, the Re was high enough that a vortex did not resolve; however, without further investigation, this cannot be stated categorically.

5.4.2.2 The upper limits skimming flow in the grike

When the simulated grike extended over the crucial W/H=0.6 aspect ratio, the skimming flow was lost and the flow transitioned to become a wake interference flow. In a wake interference flow, the vortex created by the flow separation did not reach Side B but caused a large amount of turbulence between two less stable vortices (Baik & Kim, 2002). As the grike widened further, the vortices sides at A and B were disturbed less by the surface flow. The surface flow entered the grike only momentarily before exiting. This type of flow is called an isolated roughness flow (Chang & Meroney, 2003).

5.4.2.3 Beyond the upper vortex in the deeper grikes

In a street canyon, the aspect ratio dictates the shape and number of vortices within the canyon (Jeong & Andrews, 2002). A canyon which has a W/H of 1 has only a single vortex, and a canyon with a W/H of 0.5 (twice as high as wide) has two vortices (Baik & Kim, 1999). A further vortex is added when the W/H is reduced to 0.29, in this case, the middle vortex is the largest, and the upper vortex is the strongest (Baik, Park, Chun & Kim, 2000; Murena, Favale, Vardoulakis & Solazzo, 2009; Fernando, 2012). The vortexes becoming increasingly weak with depth were observed in the deeper grikes of this simulation. Weaker flows farther from the surface have been hypothesised to exist in exceptionally deep and wide grikes in Canada, where it is stated that the body of air in lower areas of grike retain relative humidity and temperature. The difference in microclimate was theorised to be due to the lack of air mixing with the surface, and also the influence of the moist surfaces within the grike (Yarranton & Beasleigh, 1969).

5.4.2.4 Disturbing the surface flow

In a simulated grike, the skimming flow was severely disturbed by the curving of the grike lip. A curve as small as 0.1m in radius could distort the vortex in the upper reaches of the grike and by 0.2m diameter; the curve had almost destroyed the formation of any vortex. Similar effects are observed in street canyon literature with the application of pitched roofs. When a pitched roof is added to a building, the typical street canyon vortex does not develop. Instead, a zone of recirculation forms at the upwind building ridge (that of side A in a grike) and spans across the canyon. As in a grike, the flows at the top of a canyon can be turbulent and sometimes partly reversed, which impedes the formation of a vortex normally seen in a skimming flow (Kastner-Klein, Berkowicz & Britter, 2004). A result of this in the canyon as in the grike is almost stagnant flow inside the deeper areas of the canyon/grike. This disturbance to flow inside the grike may be important for the microclimate of shallow wider grikes. Although roundness of the grike lip has no direct evidence of correlation to depth or width, there is evidence that mature pavements can be characterised by wider grikes and greater surface roundness (Goldie, 2006). This means that grikes with both greater width and also more curved lip may provide more stable air currents if not a more stable overall microclimate.

5.4.3 Limitations

5.4.3.1 2D

This study dealt only with two-dimensional flows in a grike. In reality, flows occur in three dimensions and are considerably more complex than those expressed in this study. In this study, two dimensions were used to limit the complexity of the interpretation of flows. Most street canyon simulations use two dimensions also for this reason; however, some do interpret the flows of air in three dimensions. These three-dimensional studies have modified the rules which govern the establishment of the three principal flows found in street canyons by accounting for side flows and flow angles (Hunter, Johnson & Watson, 1992; Baik, Park, Chun & Kim, 2000; Baik, & Kim, 2002). Despite the modifications, the three principal forms of flow outlined by Oke (1988) remain the convention (Hunter, Johnson & Watson, 1992).

5.4.3.2 Simulation simplicity

This simulation was kept as simple as possible because it is a foundational study. Airspeed in this study was limited to laminar light air that has a flow speed of 1m/s (Strangeways, 2003). This was done to limit the complexity of the interpretation of flows and reduce the Re involved. The interpretation of idealised flows within semi-realistic parameters provides isolation of the key features' impacts on flow and for generalisation across multiple limestone pavements. The simulation simplicity allowed for ideal skimming flows to be observed in the grikes and vortices to establish. In reality, wind velocities are considerably higher and more turbulent, and consequently, do not always follow the flows observed in this study exactly.

There are several factors to be acknowledged and advanced if further research were to be used to interpret the impacts of width, depth and lip curve. By using laminar flow in this simulation, the

amount of turbulence was underestimated, potentially altering a number of the flow characteristics. This problem was investigated in street canyons to discover what effects varying degrees of upstream turbulence had on the flow within a standardised street canyon with an aspect ratio of 1. This found that varying the upstream turbulence did not influence the shape of the vortex created in the canyon; however, the turbulent energy and diffusivity within the canyon were increased (Kim & Baik, 2003). The increase that was observed is focused on the downstream roof level section of the canyon, which in a grike was close to wall B at the surface level. Increased turbulent energy and diffusivity within a grike resulted in greater mixing of air between the surface and grike. So it is probable that the laminar simulation underestimated the heat transfer between the upper level of the grike and the surface.
The airspeed used in this study is considerably lower than that experienced in reality and expected to occur under the conditions of climate change (Clark et al., 2010; McVicar, Roderick, Donohue & Van Niel. 2012; Sydeman et al., 2014). Consequently, this study does not replicate the conditions expected in a grike now or in the future but does provide guidance as to how flows may occur. A similar study of street canyons investigated the effects of a variety of external airspeeds, finding that the exchange velocity between the canyon and surface was approximately 1% of upstream wind velocity (Solazzo & Britter, 2007). This means that by using a low upstream velocity, this study is likely to have underestimated the air and heat transfer between the grike and surface air. It has, however, been found that regardless of the wind-speed, the vortex number and distribution pattern remains the same in street canyons (Baik & Kim, 1999). This may also be true of grikes, but this phenomenon would benefit from further study in order to confirm this inference.

Foundational simulations such as this provide a more qualitative understanding of the flow physics inside a grike and are not intended for direct comparison with flows in the real world. It is hoped that this study presents the potential for airflow within grikes under the tested conditions, and that future researchers will use this work to continue to explore the fluid flow of the grike microclimate.

5.4.4 Future study

This study has provided the foundations for CFD study within the grike environment. From this starting point, there are several avenues which could be explored to produce informative simulations which could inform further management.

5.4.4.1 Increased realism

In the limitations to this study, it has been discussed that this is a foundational study which has sacrificed elements of realism to limit the complexity and produce generalised results to be used by multiple pavements. A future study could take inspiration from the simulation of the street canyon to increase the realism and specificity of grike simulations. These innovations could include the introduction of upstream turbulence, increased wind-speed, three-dimensional simulation, manipulating the texture of the wall or even recreating the grike in a wind tunnel to be more representative of reality (Baik & Kim, 2002; Kim & Baik, 2003; Yang, 2016). These innovations not only progress the accuracy of grike simulation but also introduce the possibility of bespoke simulation for individual pavements.

5.4.4.2 Extreme places and phenomena

Further research based on the simulations of this study could simulate extreme conditions which are possible on a wide range of sites. This type of research is already being conducted to simulate the urban environment under the influence of predicted heatwaves (Gromke et al., 2015) and high winds (Bett, Thornton & Clark, 2017).

5.4.4.3 Windbreaks and grazing

Windbreaks have been posited as a possible measure to reduce the impacts of a predicted future with higher wind-speed. Willow and juniper scrub are recommended for upland pavements and could provide such a windbreak (Blakesley & Buckley, 2016) (Joint Nature Conservation Committee, 2009). However, without grazing management, pavements may suffer a loss in biodiversity from too great an influence from larger scrub (Moles, Breen & O'Regan, 2005). CFD research could be used to predict the ameliorating effects of different types of windbreak from scrub (Brown, 2011; Bitog et al., 2012). This may, in turn, lead to further research to understand the optimum grazing strategies needed in the future in order to maintain an ideal level of scrub.

5.5 Conclusion

It has been possible to identify several features which could be advanced upon in order to be of use to land managers in the future by simulating the wind over the surface of a limestone pavement and observing how the air moves within the grike.

The most apparent observation of airflow in the simulated grike is that the bottom of a grike is more stable than at the surface. The stability of the grike is a consistent feature of this study but bears repeating, as this is the feature which may be instrumental in creating the grike microrefugia. The stability of a simulated grike is strongly linked to the width to depth ratio. The vortex at the surface of the grike extends for a maximum of two grike width distances into the grike depth. The depth to which a primary vortex extends means that for the simulated grikes in this study, which have been between 20 and 30 cm in width, the air below 40 to 60 cm is considerably more stable than the air above that depth. This creates the possibility for another instance of a grike zonation, with a region of more turbulent air typically forming above 60cm in the grike. This zone has been observed as an area of rapid temperature change, high light fluctuation and high relative humidity change in the grikes from which microclimate data were taken. It is possible that the more turbulent airflow influences both the temperature and relative humidity change at this depth as proposed by Yarranton & Beasleigh (1969). The repeated zonation within a grike creates the possibility that different classes of grike could be created for use by land managers although these classes may need augmentation based on the increased protection afforded by a curved grike lip.

In addition to providing initial insight into the airflow within grikes, this chapter has introduced a new tool with which to investigate the grike microclimate, as to the author's knowledge this is the first study to use CFD in the context of grike microclimates. CFD is slowly entering into use by non-engineers in the fields of ecology and geology (Shengwei, 2014); however, the use of these methods outside of engineering is by no means mainstream. By using CFD in the context of grikes, this thesis has joined a small number of other authors in building trust in alternative methods for understanding habitats.

6. Microclimate simulation

6.1 Introduction

6.1.1 Climate change

The increasing concentration of greenhouse gases in the atmosphere due to the cumulative use of fossil fuels and industrial-scale farming is having wide-ranging impacts on the climate of the planet (Pachauri et al., 2014). The specific impacts which are occurring in Britain and Ireland are dealt with in greater detail in Subsection 2.4.4. Climate projection data for this chapter has been sourced from UKCP18/ RCP8.5. This data set contains the most precautionary scenario for future emissions where the world chooses not to switch to a low carbon future. Under this scenario, Annual temperature is expected to increase by 3.7°C (5th percentile = 1.7°C, 95th percentile = 6.1°C) between 1981-2000 and 2080 – 2099. Precipitation is projected to change in winter by +28% (5th percentile = -2%, 95th percentile =+68%) and in summer by -33% (5th percentile = -70%, 95th percentile = +4%) over the same time period.

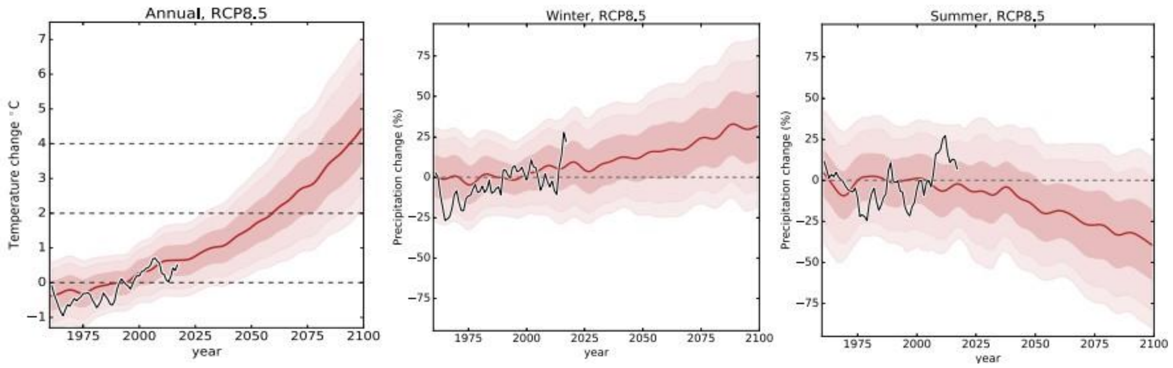


Figure 6.1 UK temperature and precipitation differences from 1981-2000 average, shading boundaries show the 5th, 10th, 25th, 50th (median, central solid line), 75th, 90th, and 95th percentiles (Murphy et al., 2018).

6.1.2 Scale of climate change projections

Climate change predictions reduce in confidence as resolution increases beyond the resolution for which projections were intended (Flato, 2013). When local level climate projections are required, 12km scale is currently the maximum resolution available from the UKCP18 with meaningful confidence (Murphy et al., 2018) This scale of measurement incorporates both macroclimate change and a small degree of local topography to reflect the local conditions (Jenkins et al., 2009; Murphy et al., 2018). This scale provides enough resolution to understand the pressures on some species, but smaller invertebrates and plants found within grikes operate on a considerably finer scale (Potter et al., 2013).

Bioclimatic envelope models are increasingly used to understand the influences of climate change on a species survival or extinction from a current niche (Franklin, 1995). The bioclimatic envelope is a theoretical model-based niche, created through the intersection of environmental constraints and species environmental tolerances, derived from either current ranges or laboratory-based testing (Araújo & Peterson, 2012). There is a large amount of uncertainty inherent in these niche-based models due to the variability of direct and indirect effects on species from multiple climate projections (Pacifici et al., 2015; Thuiller et al., 2019). This uncertainty is dealt with in greater detail in subsection 2.4.4.2. Many of these niche models are considered over large scales from regions and nations (Pearson & Dawson, 2003) to continents (Levinsky et al., 2013). In order to generate smaller scale models, ecologists need an understanding of small-scale microclimates and their future. Modelling scale is especially important in areas which are not typical of the surrounding landscape and host niches important to areas of specialised biodiversity, such as slopes, lakes, canopy or high elevation (Bonan, 2015). The resolution of climate data is a limitation to many studies of climate change as the scale of climate modelled often does not match the scale of climate experienced by the species under study (Potter et al., 2013). Such differences in spatial scale have been shown to influence the estimated impacts of climate change on biodiversity, leading to the possibility of incorrect assumptions being made and incorrect management being carried out (Trivedi et al., 2008, Suggitt et al., 2011; Gillingham et al., 2012).

6.1.3 Modelling microclimate environments

6.1.3.1 Subterranean microclimates

Caves have received attempts to model microclimate in order to identify bioclimatic niches for bats and other subterranean species. Cave microclimate models, such as that made by Wigley and Brown (1971) are derived from cave temperature and relative humidity. This model can be used to plot the distance between the cave mouth and the region of constant cave temperature, and subdivide it based on temperature and relative humidity (Faulkner, 2013). Alongside caves, modelling has been conducted to predict the microclimate of soils using calculations of the influence of solar radiation (Bennie, Huntley, Wiltshire, Hill & Baxter, 2008). Regression models of the microclimate found in caves and the soil have also been created, using multiple external variables and internal features to shape predictions (Kang, Kim, Oh & Lee, 2000; Jernigan & Swift, 2001). Though not yet used to predict future microclimates, such models have the potential to be used to project future scenarios. The equations used to describe caves and the soil benefit from a long history of research, whereas grikes are only recently receiving the long-term research required for this level of understanding. Chapter Four of this study has provided a long-term data set from which to generate a probabilistic simulation of the grike microclimate upon which to base future models the grike temperature. This study has also provided a more mechanistic understanding behind the stability of the grike microclimate by advancing the work of previous grike microclimate authors such as Alexander, Burek & Gibbs (2007).

6.1.3.2 Periodicity

Periodic shifts in temperature are common to many microclimates. Similar yearly fluctuations in temperature have been observed in caves (Hall, 1982; Hoyos et al., 1998) and daily fluctuations observed in a forest (Chen, Franklin & Spies, 1995; Davies-Colley, Payne & Van Elswijk, 2000). This periodic nature has allowed some to model such environments using sinusoidal functions. Such models have been employed when modelling the temperature of soils (Marshall, Holmes & Rose, 1996; Kang, 2000) identifying the temperature as a function of time and depth. Further models have exploited the periodic nature of daytime temperatures to model forest microclimates through linear regression, using time among other functions (Didham & Lawton, 1999; Saunders et al., 1999).

6.1.3.3 Simulating the microclimate of the grike

While it has been shown from the limitations in Chapter Four that there is insufficient data on a wide enough sample of grikes to allow prediction with a high level of confidence. It is possible to simulate the grike temperature using the same techniques as would be used in a model. To create an informative scenario based on IPCC projections and the data from this study, which is more extensive than any other known by the author.

Chapter Four details the patterns observed in the microclimate data that indicate that surface temperature, grike orientation, grike depth and month of the year are the strongest predictors of temperature in the grike. Based on the available variables, their effect on grike temperature and the research from this introduction, it is indicated that linear regression using a variety of parameters may be an effective method of creating a simulation of grike temperature. From the observations in Chapter Four, it was possible to identify how each variable contributed to creating the grike microclimate.

Surface temperature – correlations between the temperature at the surface and within the grike identified that these two temperatures have a positive linear relationship. This relationship forms the baseline for the simulation as this linear relationship describes the behaviour of the system in its simplest form (Jernigan & Swift, 2001).

Month – The difference between the temperature at the surface and the temperature within the grike is positive during the summer and negative during the winter. The month is a categorical variable in this regression, and in order to represent the changing difference in temperatures, month additively influences the grike temperature.

Depth - Depth directly influences the magnitude of impact the surface has on the grike temperature. At greater depth, the impact of temperature change is a fraction of that at the surface. In order to represent the relationship depth has on surface temperature, depth has been used to reduce the surface temperature using a multiplicative relationship.

Orientations – Orientation of a grike has a complex relationship with surface temperature, and with both month and depth. The average temperature of the EW grike is greater than that of the NS grike; however, the effect of orientation on grike temperature is minor when compared to other variables such as month and depth. Orientation has a multiplicative relationship with depth and month in this regression; however, the inclusion of orientation could result in undue complexity.

This chapter uses the data from Phase One of the methodological structure in order to complete the 2nd phase. This is done in order to meet the fifth objective of this thesis that endeavours to produce a preliminary modelling exercise to provide a temperature simulation of the future grike microclimate. This simulation is used to provide a probabilistic scenario of the grike microclimate over the next century in order to formulate an evidence base from which to discuss future research needs. This chapter also contributes to the evidence on which to discuss the microrefugial potential of the grike.

6.2 Methodology

6.2.1 Microclimate data

Microclimate data for analysis were taken from the data used in Chapter Four. Data were categorised by grike orientation, logger depth and time of logging to include the year, month, day and hour. Data were subjected to testing for regression suitability, following the methodology laid out by Zuur, Ieno & Smith (2007). The temperature data was found to violate the condition of homogeneity of variance. In order to overcome this issue, provide more easily interpretable data, the data were averaged by mean for each month before further analysis.

6.2.2 Analysis of the grike temperature simulation

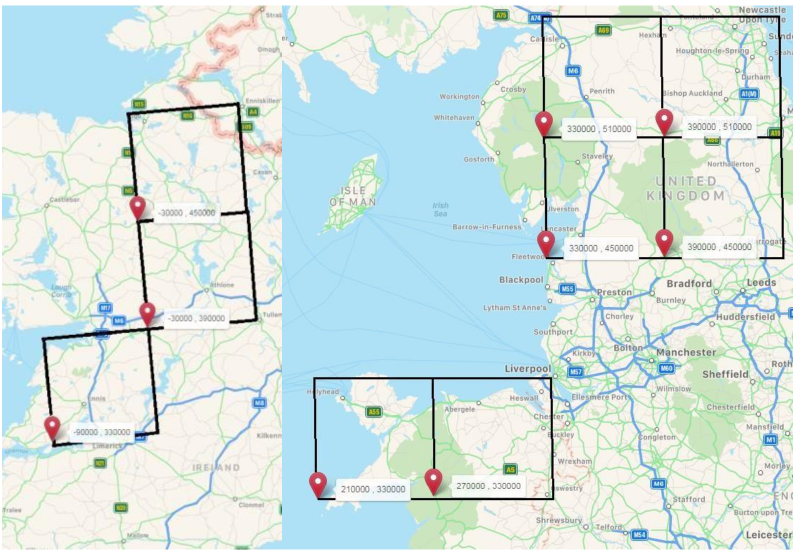
The analysis was completed using the "stats" package in R. The linear regression function was used without polynomial expressions because the relationship between surface temperature and temperature in all depths of the grike is linear, as shown in Chapter Four.

Several regressions were fitted to the data using a stepwise forward selection approach (Draper & Smith, 2014). This procedure starts with a baseline with no additional variables and sequentially increases variables until the most effective version is created. The suitability of the simulation was selected using Akaike Information Criterion (AIC) following the methodology in Burnham & Anderson (2003), and coefficient of partial determination or partial R^2 has been used to assess the marginal contribution of each explanatory variable (Ferrier & Guisan, 2006). When the significance of the regression predictors was tested, a statistical significance of 0.05 was used.

Cross-validation for testing the simulation was completed using the k-folds method where k=10 random folds. This method creates k random subsets and sequentially conducts a test and train evaluation of the data. This method has the benefit of evaluating the accuracy against a wider sample of the data set when compared to holdout cross-validation, it is also considered an efficient use of resources (Burger, 2018). Computations used the k-folds for linear regression (cv.lm) function from the DAAG package in R (Maindonald & Braun, 2015). The simulation was tested further by comparing the simulated scenario to those collected in Chapter Four using a series of descriptive plots.

6.2.3 Analysis of the climate projections

In order to project the microclimate of the grike into the future, surface temperatures in the grike simulation were replaced by absolute mean temperature data from the UKCP18. The projections used were derived from the 15 CMIP5 models created by the Hadley Centre for emissions scenario High (RCP8.5) for all calendar months from 2010 to 2099 (Murphy et al., 2018). These future scenarios were taken from UKCP18 60km grid locations for the Northwest of England, North Wales and the west of the Republic of Ireland. URL references of each data set used can be found in Appendix 2. The locations used contain the largest clusters of limestone pavement in Britain and Ireland and contain all limestone pavements used in this study. This selection cannot be claimed to be representative for all limestone pavements in Britain and Ireland; however, this detail is discussed further as a limitation to this study. The projections used in this study have been sourced from the Hadley centre's 15 simulations, which provide "a range of future CO^2 pathways, consistent with uncertainties in how carbon cycle feedbacks convert emissions in the RCP8.5 scenario into atmospheric concentrations" (Murphy et al., 2018). The resolution of 60km was used as opposed to the finer 12km resolution, because it is recommended that larger grid squares should be used when making more general projections for a wider area (Murphy, 2018). The RCP8.5 scenario was used in this study because of the limits to available data at this time; the use of further emissions scenarios is covered in the discussion of this chapter.



Anglesey:	210000, 330000
Burren:	-90000, 330000
Cumbria:	330000, 510000
Denbighshire:	270000, 330000
Leitrim:	-30000, 450000
Lancashire:	330000, 450000
Roscommon:	-30000, 390000
North Yorkshire:	390000, 510000
South Yorkshire:	390000, 450000

Figure 6.2 Grid locations used in climate projections (Met Office, 2009).

The projected microclimate of the grike was described using a series of line and box plots. These illustrated the projected rise in macroclimate temperature in the various $60km^2$ locations and the projected temperature rise within the grike when compared to the surface.

6.3 Results

6.3.1 Regression selection

As stated in the methodology, the process of selecting a regression followed a stepwise progression, using AIC to indicate suitability. The resultant combinations of variables are described in Table 6.1.

Table 6.1 Resultant variable combinations from the stepwise selection.

Combination ID	Explanatory variable(s) used	AIC	Δ AIC
8	Month + (Surface temperature * Depth)	4234.39	268.08
9	Surface Temperature + (Depth * Month)	4039.78	73.47
10	Surface Temperature + (Depth * Month * Orientation)	3966.31	0

The final three variations were subjected to K-fold cross-validation (Table 6.2) in order to test their effectiveness on a subset of the test sample.

Table 6.2 k-fold cross-validation of the three final candidate variable combinations.

Combination ID	root-mean-square error	R^2	mean absolute error of prediction
8	0.7132585	0.9753322	0.5407493
9	0.6797574	0.9774553	0.5006854
10	0.6562616	0.9788889	0.4830343

Both AIC and R^2 show that combination 8 was least effective and that interaction between month, depth and orientation in combination 10 was most effective. Cross-validation of each of the combinations identified that root-mean-square error and mean absolute error of prediction was lowest for the 10th combination of variables. This indicated that this combination most accurately predicted grike temperature values in the repeated subsets of the data. Table 6.3 shows that the surface temperature had the most influence on the R^2.

Table 6.3 Partial R-Squared value for the final two candidate combinations.

Variable β	partial R^2 value	
	Variable combination 9	Variable combination 10
Surface Temperature	0.8652	0.8300
Month	0.1623	0.1466
Depth	0.0130	0.0103
Orientation		0.0097
Month * Depth	0.3880	0.3845
Month * Orientation		0.0320

The combination of variables to be taken forward was number 10. This variation used depth, month, orientation and surface temperature to predict grike temperature for a given depth and orientation on a given month. It was found that the regression equation predictors were significant when compared to an intercept only simulation ($F\ (96, 1859) = 961.6$, $p < 0.05$) and the fit provided an R^2 of 0.98. The surface temperature was equal to 0.75 + 0.78 (surface temperature) + (depth * categorical month variable) (Table 6.4), where surface and grike temperature were measured in °C, and depth was measured in cm. Where the grike temperature increased 0.78 °C for every 1°C at the surface and each centimetre of depth either increased or decreased the temperature depending upon the month of the year and orientation (Table 6.4). The surface temperature was a significant predictor of grike temperature, whereas all months apart from January, October, November and December joined with Depth to create a significant predictor variable in the EW orientation (Table 6.4). The NS orientation provided no significantly different values.

Table 6.4 Parameter estimates and test statistics for the generalised linear recreation explaining temperature at a given depth and orientation of a grike. One level of each categorical variable serves as a contrast (β = 0) for the remaining levels of that variable.

	Estimate	Std. Error	t value	Pr(>|t|)
Surface Temperature	0.7825	0.00819	95.541	<0.05
Depth:EW:January	0			
Depth:EW:February	-0.00282	0.00206	-1.369	0.17114
Depth:EW:March	-0.00628	0.002171	-2.892	<0.05
Depth:EW:April	-0.016	0.002171	-7.37	<0.05
Depth:EW:May	-0.01944	0.002113	-9.2	<0.05
Depth:EW:June	-0.02921	0.002171	-13.451	<0.05
Depth:EW:July	-0.0315	0.002171	-14.505	<0.05
Depth:EW:August	-0.01509	0.002171	-6.95	<0.05
Depth:EW:September	-0.01044	0.00206	-5.068	<0.05
Depth:EW:October	-0.00259	0.002061	-1.256	0.20944
Depth:EW:November	0.00148	0.002061	0.718	0.47283
Depth:EW:December	0.000699	0.002035	0.343	0.73128
Depth:NS:January	-0.00188	0.00206	-0.914	0.36071
Depth:NS:February	0.000807	0.002914	0.277	0.78174
Depth:NS:March	0.000197	0.003071	0.064	0.9488
Depth:NS:April	0.002493	0.003071	0.812	0.41693
Depth:NS:May	0.001957	0.002988	0.655	0.51251
Depth:NS:June	0.004509	0.003071	1.468	0.14217
Depth:NS:July	0.003512	0.003071	1.144	0.25285
Depth:NS:August	0.000646	0.003071	0.21	0.83347
Depth:NS:September	6.92E-05	0.002914	0.024	0.98107
Depth:NS:October	-0.00067	0.002914	-0.228	0.81933
Depth:NS:November	0.000446	0.002914	0.153	0.87847
Depth:NS:December	0.000819	0.002877	0.285	0.77587

6.3.2 Future grike temperature scenario

6.3.2.1 Current grike temperature

The grike microclimate was simulated under current climate conditions using the UKCP18 climate data. Figure 6.3 a and b both show boxplots of the temperature in the grike taken from a variety of depths over a year. Figure 6.3 a shows the measured results taken from Chapter Four and Figure 6.3 b shows the simulated grike temperature. There were several differences between the simulated and the measured results. The variance, in reality, was greater than that in the simulated data; however, the simulation did reduce variance as depth increases as was observed in measurements from Chapter Four.

The simulation produced a more regular association between depth and temperature than was observed in measurements from Chapter Four; however the relationship observed, in reality, was replicated through the simulation without overfitting (Zuur, Ieno & Smith, 2007).

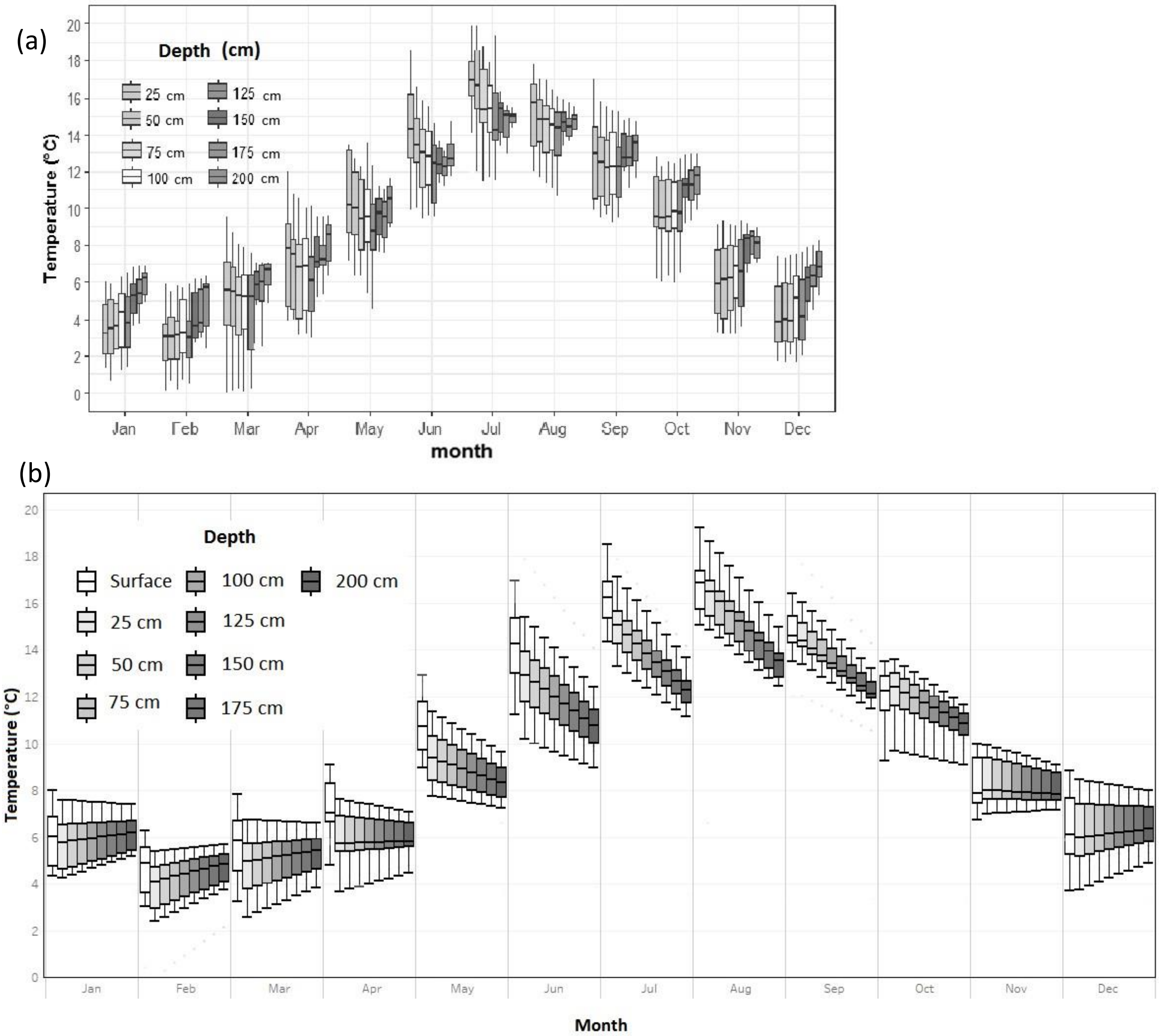


Figure 6.3 Recorded grike temperatures from the current study (a) compared to the mean of both orientations from the grike simulation which has been applied to current UK climate data taken from the UKCP18 2018 baseline data (b).

6.3.2.2 The effect of grike orientation on the temperature in the simulation

The simulated mean yearly temperature in the EW grike was calculated to be higher than the NS grike, and the temperature difference was calculated to be higher with depth (Figure 6.4). In Subsection 4.3.2.6, Figure 4.13 describes a similar behaviour from the measurements taken from the grikes. The measured results indicated a higher temperature in the NS grike than the EW grike after 175 cm, which was not described by the simulation. The simulated mean monthly temperature showed a complex relationship between month, depth and orientation, such that the difference in temperature during the summer decreased with depth (Figure 6.5). This behaviour is described in figures Figure 4.15 to Figure 4.17. The measured results showed that the NS grike was warmer than the EW grike during the summer at 200 cm. However, this was not shown by the simulation. The temperature calculated for the different orientations of grike was very similar. For this reason, all further figures in the chapter show the means of the two orientations.

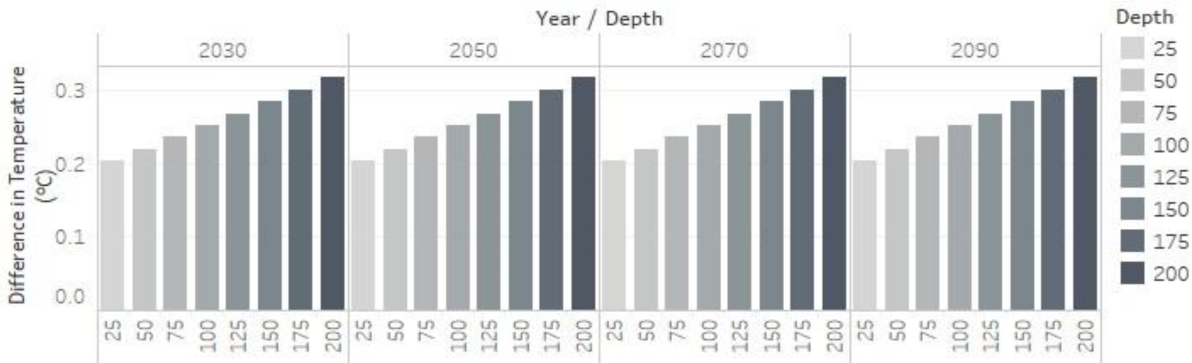


Figure 6.4 Mean difference in the simulated temperature between the two grike orientations (NS grike subtracted from EW grike) at all depths of the grike for a year from 2030 to 2090.

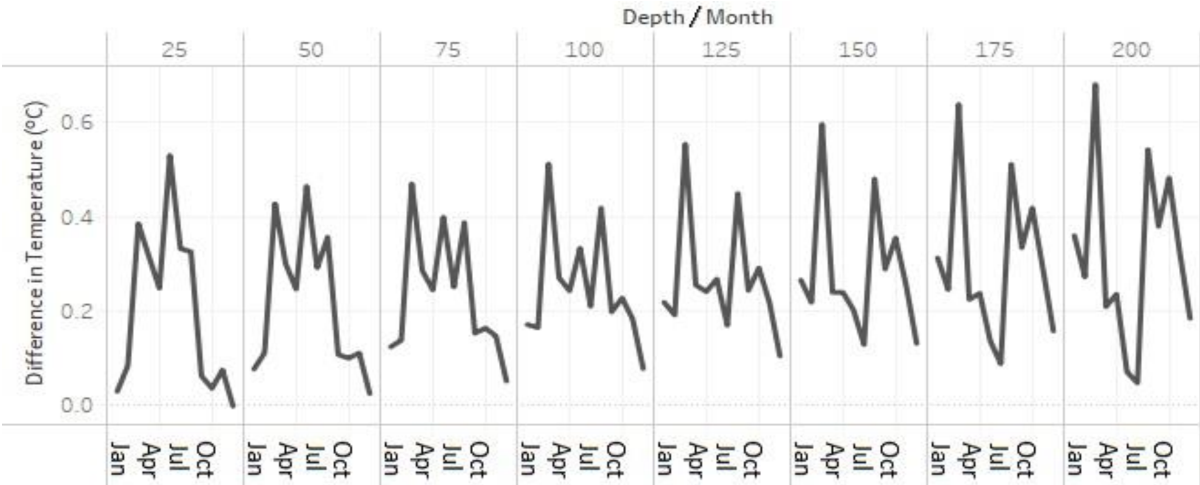


Figure 6.5 Mean difference in simulated temperature between the two grike orientations (NS grike subtracted from EW grike) at all depths of the grike for a month from 2020 to 2100.

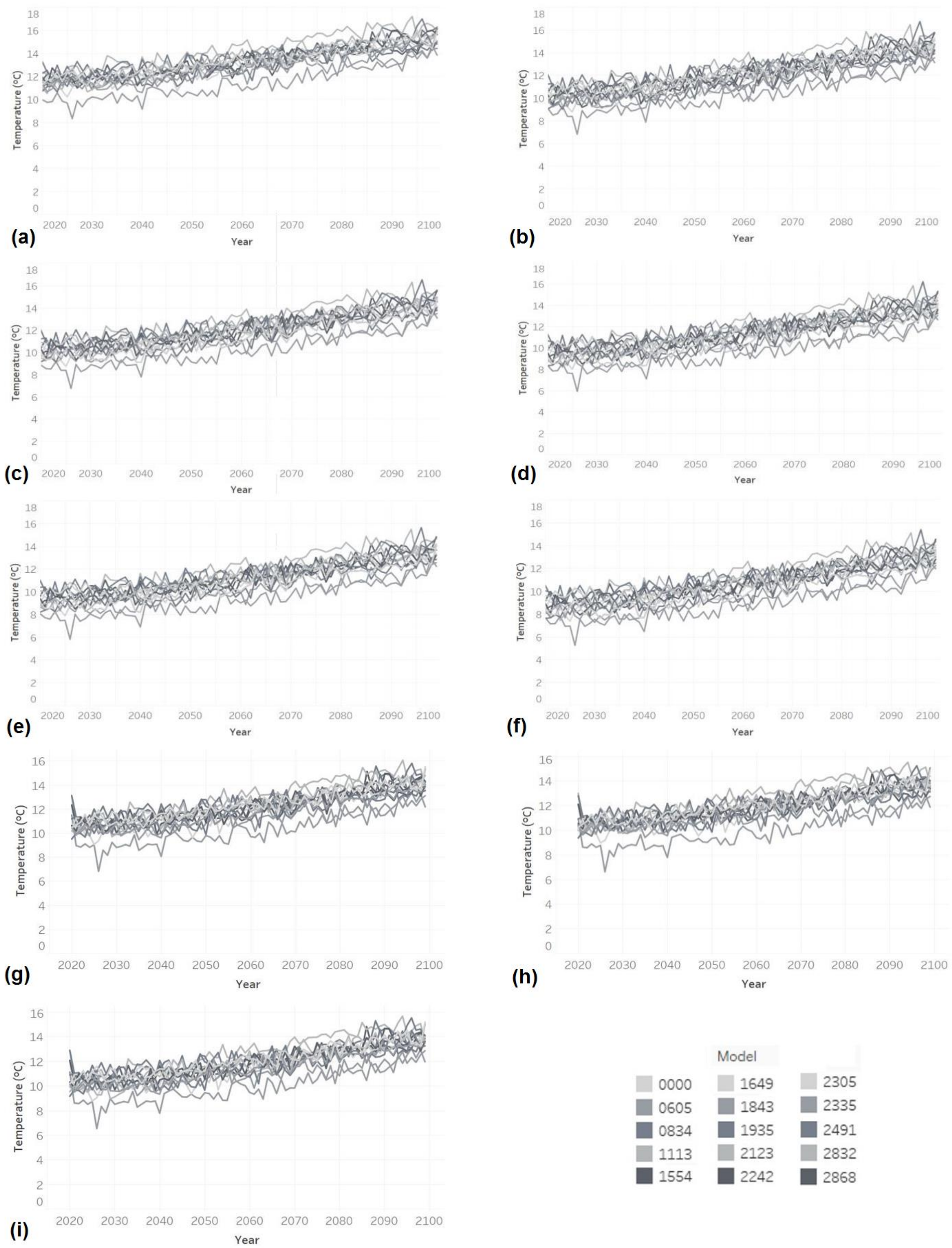


Figure 6.6 Projected temperatures for the 15 CMIP5 models for emissions scenario RCP8.5 between 2020 and 2099 for six limestone pavement regions of the UK. In order of decreasing temperature (a) Anglesey (b) Denbighshire (c) Lancashire (d) South Yorkshire (e) Cumbria (f) North Yorkshire (g) Burren (h) Leitrim (i) Roscommon

6.3.2.3 Future grike temperature

The future climate projections from the IPCC used in this study were sampled from 60km squares located in the areas of highest limestone pavement density in Great Britain and the Republic of Ireland. These areas have slightly differing temperature projections, for example, the Isle of Anglesey is projected to experience the greatest temperature, and North Yorkshire is projected to experience the lowest temperature. The projections made in this study were from the UKCP18/RCP8.5 high emissions scenario, which is shown in Figure 6.6. While this is considered of equal likelihood to other outcomes, it is a very high baseline emission scenario (Pachauri et al., 2014).

In order to observe the effect of time on the grike microclimate over the selected areas, the UKCP18/RCP8.5 was modelled for the years 2030, 2050, 2070 and 2080 and a mean for all locations was calculated. The results for each depth were then plotted in a boxplot for each month of the year to provide a representative summary for grikes in the selected areas (Figure 6.7)

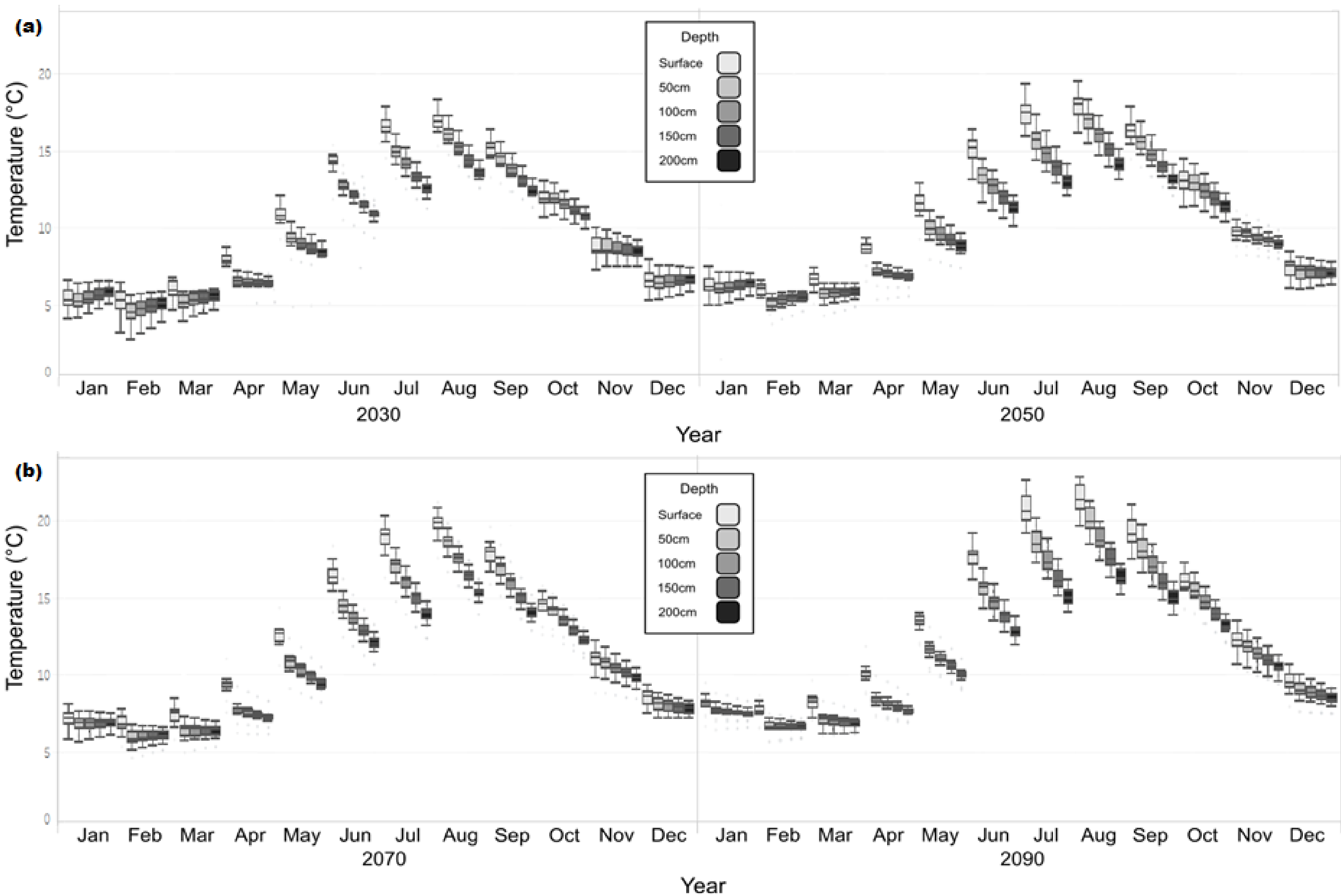


Figure 6.7 Mean of the calculated temperature from grikes in the years 2030, 2050 (a), 2070 and 2090 (b) for the 15 Hadley centre climate models under UKCP18 high emissions scenario (RCP8.5).

By plotting the high emissions scenario for the grike microclimate, it is possible to observe that at the surface, the increase in temperature was considerably more rapid than within the grike. This occurred most prominently during summer where the median temperature between 2030 and 2090 was calculated to increase by 0.73°C per decade at the surface and, 0.58°C and 0.45°C per decade at 100cm and 200cm respectively. The difference in the rate of warming resulted in a widening difference in temperature between grike and surface as time progressed. In the summer of 2030, there was as much as 4.02°C difference between the surface and 200cm, and by 2090 this had increased to 5.66°C difference (Figure 6.8).

This difference in temperature is shown explicitly in further plots in Figure 6.8. These plots demonstrate the increasing disparity between the temperature at the surface and temperature within the grike calculated for 50cm (a) and 200cm (b).

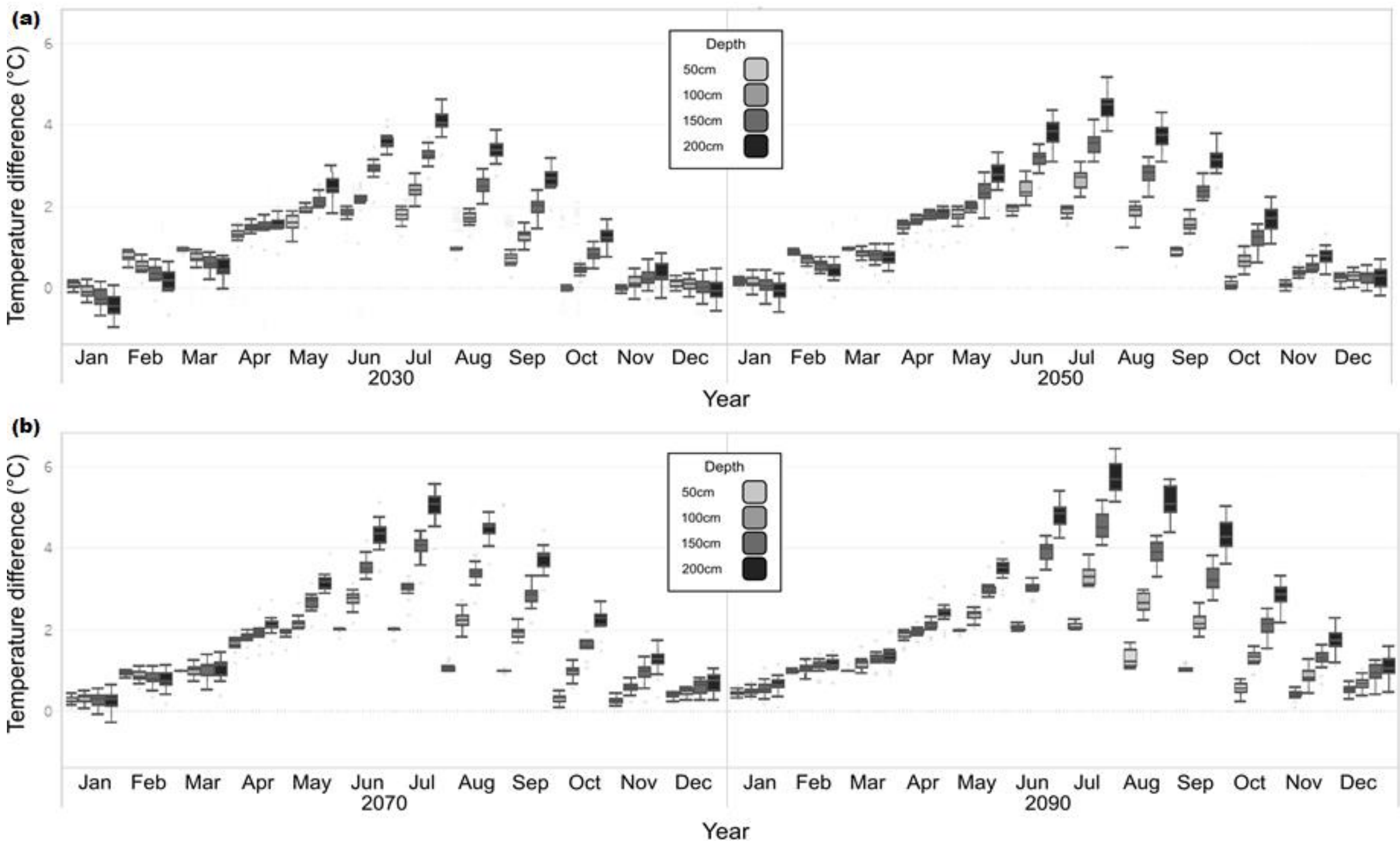


Figure 6.8 Difference between the surface temperature and the mean calculated temperature from grikes in the years 2030, 2050 (a), 2070 and 2090 (b) taken from between 50cm and 200cm for the 15 Hadley centre climate models under UKCP18 high emissions scenario (RCP8.5).

6.4 Discussion

6.4.1 The grike simulation

Throughout this study and simulation process, there has been a growing evidence base on which to suggest that the grike microclimate is the product of the regional macroclimate. This macroclimate has been observed to be modified by depth in different ways depending upon the orientation of the grike. The depth and orientation of a grike have both been observed to impact the grike microclimate differently depending on the regional climate, which is in turn affected by the time of year. This relationship has been refined to create the simulation which was shaped in this chapter.

The surface temperature served as a foundation upon which to base the linear regression used in the simulation, as the results showed that surface temperature had a large influence on the grike microclimate compared to other variables in this study. By using surface temperature as a foundation for the model, it was possible to understand further how energy entering a system affected microclimate. Finding the relationship between external and internal climate is often the goal of microclimate studies (Jernigan & Swift, 2001).

The depth function in the linear regression served to influence the grike temperature in relation to the surface, by affecting the surface temperature by greater fractions as depth increased. This influence was not strong on its own, but when interacting with the month, produced the second greatest effect on the outcome of the simulation. A similar relationship between surface temperature, microclimate temperature and depth can be observed in the model of cave microclimates created by Wigley and Brown (1971). In this way, the distance from the external environment helps to determine the gradient of temperature change (Saunders, Chen, Drummer & Crow, 1999). The categorical variable of orientation of the grike decreased the AIC by only a small amount compared to other variables and this difference was not statistically significant.

The impact of the categorical month variable served to increase or decrease the effect that depth had on the surface temperature in order to produce the grike temperature. In the linear regression used in the simulation, the month had an impact only slightly greater than that of depth; however, when combined, the effect on the fit was larger. The month variable is used to generate multiple categorical regression coefficients in cave microclimate models. These interact with spatial components of the location of the cave to both increase and decrease the temperature of the cave depending on the time of year (Halbert, 1983). This influence shows that the cave temperature can be greater than or less than that of the outside temperature depending on the month of the year, as was calculated by the grike microclimate simulation.

6.4.2 Grikes and climate change

6.4.2.1 Interpretation of the simulation

In recent years there has been a greater call for research to investigate the fine-grained effects of climate change which directly disturb species' habitats (Gillingham, Huntley, Kunin & Thomas, 2012; Franklin et al., 2013). This chapter has indicated that the limestone pavement grike may prevent or delay a certain amount of the projected short-term temperature change from taking place within the grike microclimate and hypothetically reduce the risk to species. This delay is even the case within the upper zone of the simulated grike, which while providing less shelter, produces a meaningfully different microclimate from the surface at only 25cm in depth. Such a large difference was not observed in the grikes temperature, measured in Chapter Four. This may indicate that there is a greater divergence between the grike and external climates and may provide microrefugia conditions (Pike, Pepin & Schaefer, 2013).

Despite the apparent distance between the grike microclimate and the macroclimate of the region, there is still an impact of long-term climate change on the simulated grike microclimate. The grike microclimate is indicated to slow the onset of climate change in the grike; the magnitude of this lag depends on the grike and severity of change at the surface. The lag observed in the simulation is comparable to delays in temperature change measured in soils in Canada taken from between 5cm and 150cm (Qian et al., 2011). Other habitats such as caves also experience lags in temperature change dependent on the depth from the surface. Shallower caves such as Eagle Cave situated under a small hill in Ávila, central Spain experience changes in climate after a delay of three to ten years (Domínguez-Villar, Fairchild, Baker, Carrasco & Pedraza, 2013). Deeper caves such as the 37m deep Postojna Cave in Slovenia experience a delay of 7 to 15 years (Domínguez-Villar et al., 2015).

In Chapter Four and five, it was observed that limestone pavement grikes share commonalities with forest ecology and a street canyon microclimate. These commonalities may currently be observed over shorter time scales where diurnal changes and the severe weather events are more keenly observed.

6.4.3 Limitations to the grike simulation and future research

6.4.3.1 Limitations

Though this simulation serves the purposes of this study and provides an indication of the microclimate expected in the future, there are limitations to the simulation which must be discussed.

6.4.3.1.1 Zonation

Throughout this study, it has been highlighted that there are two zones to the grike microclimate with different levels of stability, divided by a transition zone. This simulation does not reflect this zonation. This is largely because the grike simulation summarises the mean grike temperature over a month, whereas the zonation hypothesis predicts zones of temperature fluctuations over the short term. Further simulations and models with a higher temporal resolution may include zonation as a predictive variable in addition to depth.

6.4.3.1.2 Delay in temperature change

In Subsection 4.3.2.3, delay in temperature change was explored as it related to grike depth. This indicated that there was in an increasing delay to the temperature changes experienced at the surface, as depth increased. This fact was not borne out by the simulation created by this study, because of the time scale over which the delay occurred. In Subsection 4.3.2.3, it was observed that in the summer, the temperature change was delayed by hours over a depth of 175cm; however, the simulation created is too low in temporal resolution to account for this feature.

6.4.3.1.3 Emissions scenario and geographical coverage

At the time of writing, the UKCP18 absolute temperature data available for use is limited to values for only the high emissions scenario (RCP8.5) over 60km^2 and 12km^2 grid locations. Further data is scheduled to be released when available, allowing future simulations and models to provide a wider range of possible emission futures. By using the high emissions scenario, the simulation used shows the warmest plausible scenario for the grike microclimate and that which deviates most greatly from the current microclimate. It is beneficial that this scenario was available, as this shows that the grike microclimate remains relatively stable when compared to the IPCC's worst-case outcome. The IPCC, however, consider all RCP emission scenarios to be equally likely emphasising that "no likelihood or preference is attached", and therefore all scenarios should be considered in future simulation or modelling work (Pachauri et al., 2014). The inability to include other climate scenarios in this study may lead to a misrepresentation of the severity of the changes which are expected to occur in the future. As such, this study has emphasised that the simulations made are derived from the high emissions scenario and that future work should be conducted that use all other emission scenarios.

The nine 60km^2 grid squares from which the UKCP18/RCP8.5 climate projected were sourced, represent the largest concentrations of limestone pavements in Great Britain and the Republic of Ireland. This has resulted in some areas such as the southwest of Ireland and the north of Scotland not to be included in the climate simulations created by this study. Likewise, the grikes used to collect the microclimate data on which the initial microclimate simulation is based, are limited to five sites in the northwest of England and The Burren. The geographical representation of the microclimates measured in this study is discussed in Subsection 3.3.3.2. Were all sites to have been included in the analysis this would have introduced a larger number of coastal climates into the study that is atypical of most limestone pavements. The implications of the geographical limitations of this study are that there is a lower confidence with which assertions may be made about grike temperatures for sites outside the sampled area.

6.4.3.2 Future research

This simulation has progressed the understanding of the impacts of climate change niche habitats by downscaling the UKCP18 climate model to apply specifically to limestone pavement grikes. By simulating the temperature in this habitat, the groundwork has been provided for future study which may inform the future management of limestone pavements.

Future research to identify the implications of climate change could utilise the EURO-CORDEX climate projections for the Republic of Ireland and UKCP18 regional projections for Britain and Ireland (Olbert, Dabrowski, Nash & Hartnett, 2012). These could be used to refine the simulation used in this chapter and identify regional variations for limestone pavement grikes over a greater number of emissions scenarios as and when data become available. It is anticipated that continued research will supersede this simulation as it is refined by the continued data collected by data loggers left in place at the end of this research. Future research would also benefit from simulations or models with a higher temporal resolution, capable of viewing the changes to diurnal temperature change in the future. Work of this type may add value by incorporating the zonation hypothesis outlined in this thesis.

In Subsection 4.4.10.2 it is suggested that further sites be included in any subsequent microclimatic study of grikes. This chapter has identified that areas such as the Isle of Anglesey in North Wales have a warmer climate than other areas of the UK, and if this study were to be expanded data from sites such as this may give a more representative idea of the future of the grike microclimate.

Existing pressures on the grike habitat were detailed in Subsection 2.4.3 and identified the impacts that inappropriate grazing, "undesirable" species and human activity can have on the grike. Effects such as these, do not act independently of climate change and may intensify one another (Ackerly et al., 2010). To the author's knowledge, there is limited research available to understand how these issues may be exacerbated or diminished by the effects of climate change. The findings from this chapter and any subsequent simulation may usefully be used to better understand how changes in the microclimate of the grike may interact with other non-climate pressures.

6.5 Conclusions

By simulating the grike temperature, this study has made further steps toward understanding the interaction of macroclimate and grike structure in the creation of the grike microclimate. In this way, it has made it possible to quantify many of the assertions made in Chapter Four to produce a basis on which to create simulations of the future temperature of the grike. Past chapters have shown that while over the short term the grike bears resemblances to forest or street canyon protective microclimates, simulation of the grike microclimate temperature have shown that over the longer term grikes may delay the onset of temperature rises, which is more like the microclimates of caves or temperature change observed in deep soil.

When both short- and long-term temperature changes are taken together, it remains possible that the grikes may provide a protective microclimate suitable as microrefugia, but like many others will become warmer in the long term.

7. Invertebrate fauna

7.1 Introduction

7.1.1 Microclimate and species distribution

Plants and animals evolutionary histories have resulted in their individual preferences for certain climates (Marks & Lechowicz, 2006; Johnson, 2017). Ectotherms such as insects, crustaceans and molluscs are particularly vulnerable to changes in temperature because of their inability to regulate their temperature internally. The ability of ectotherms to function at different temperatures is often described by a thermal performance curve (Huey & Stevenson, 1979).

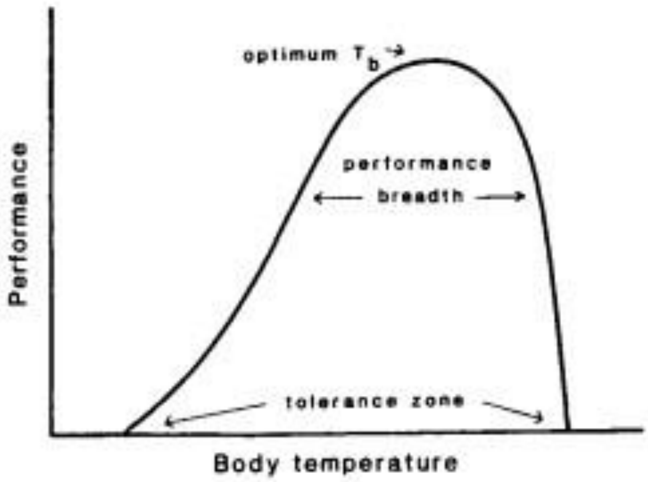


Figure 7.1 Thermal performance curve (Huey & Stevenson, 1979).

This curve describes an increase in physical performance as temperature increases up to the point of optimum performance; however, as temperature increases past the optimum, there is a sharp decrease in performance until death occurs. Microclimates can provide an environment where species can survive or perform more optimally than would otherwise be expected for the geographic region (Gray, 2013). Currently, the grikes provide a niche to a “unique plant community which characterises the microclimates of the grikes” (Willis, 2011). The link between microclimate and biodiversity is explored in greater detail in Subsection 2.3.2 of the literature review. Such microclimates can provide an advantage within an increasingly hostile climate which could be considered harmful to vulnerable species or place them at a disadvantage when competing with other species for resources, and have the potential to provide microrefugia (Ashcroft, 2010; Dobrowski, 2011).

7.1.2 Species surveying in grikes

Ecological studies of limestone pavements have mostly been concerned with the plant life found within grikes (Webb, 1947; Ward & Evans, 1976; Gauld & Robertson, 1985; Margules, Nicholls & Usher, 1994; Deacon & Burek, 1997; Lundholm & Larson, 2003; Thom et al., 2009). Of these, Silvertown (1983) presents the most persuasive argument for a link between microclimate and species diversity by directly sampling plants from a range of grike depths while investigating the microclimate.

Most of these studies of the limestone pavement fauna have involved visual surveys of those invertebrates available to investigators (Nichols, 2009; Willis, 2011). These studies examined the various effects of pavement type and form on the prevalence of different invertebrates (Lloyd-Jones, 2001; Sheehy, 2004; Swindale, 2005; York, 2009; Willis, 2011).

Willis (2011) was accompanied by a conchologist in order to assist in species identification as part of visual surveying; however, a lack of taxonomic expertise is cited as a factor limiting other fauna research (Lloyd-Jones, 2001; Swindail, 2005; Nicholls, 2009). Some studies have been able to trap invertebrates in shallow grikes using pitfalls and identify them under a microscope (York, 2009). Both the methods used in these studies limit the collection of invertebrates to the surface or very shallow grikes, and neglect the diversity of life found where the microclimate is most stable. Dissertation students conducted most studies linking grike depth or orientation to invertebrate fauna (Lloyd-Jones, 2001; Sheehy, 2004; Swindale, 2005; Nicholls, 2009; York, 2009). A summary of the findings of these studies can be found in Subsections 2.3.1 and 2.3.2.3.

A large number of the more recent studies of invertebrates within grikes have been conducted by students, as part of undergraduate dissertations or a PhD thesis. Some surveying of limestone pavement grike invertebrates has been conducted by Natural England and peer-reviewed studies and produced a small number of species lists. Species found on limestone pavements are characteristic of a woodland floor (Colbourn, 1974; Backshall, Webb & Jerram, 2001). Most studies have found a prevalence of snails, woodlice, ground beetles, millipedes, centipedes, silverfish and springtails. Some invertebrate species associated with limestone pavements are rare such as the Narrow-Mouthed Whorl Snail (*Vertigo angustior*) (Jeffreys, 1830; Killeen, 1997). This species is classified as Endangered on the UK's Red List, Vulnerable on the IUCN Red List and is included in Annex II of the EC Habitats Directive (UK BAP, 2008).

Many of these studies gave an implicit indication that microclimate impacted species distribution (Sheehy, 2004; Swindale, 2005; Willis, 2011); however none of them coupled invertebrate sampling with microclimate measurement, nor were they able to sample invertebrates directly from deeper grikes where more stable microclimates are most common. Although the studies that have taken place indicate that there is a relationship between invertebrate distribution and microclimate, to the knowledge of the author there has not yet been a study to conclusively make this link as Silvertown (1983) did when looking at plant distribution in grikes.

7.1.3 Approach

The purpose of this chapter is to discuss the research undertaken to complete Phase Three of the methodological structure. This has been done in order to establish the effect that depth, orientation and location have on the invertebrates found within a grike. These factors are informed by prior chapters making up Phases One and Two of the methodological structure. This information is used in order to fill knowledge gaps highlighted in the introduction of this thesis by hypothesising the effect that microclimate may have on the invertebrates found within grikes. This study also contributes to the little that is known of the invertebrates that live within the grikes of limestone pavements. This information is to be used to understand the type of life which may be protected by this possible microrefugium and provide initial findings which may be advanced in order to benefit the management of this habitat.

In order to complete the sixth objective of this thesis, samples of invertebrates have been extracted from several grikes. The sampling methodology has been informed by prior studies of grike invertebrates and existing literature on the topic. Sampling has been undertaken to allow invertebrates from a range of grike depths to be extracted, giving a more explicit indication of invertebrate microclimate interaction than previous studies. Specific invertebrate groups are explicitly targeted due to their prevalence within the grike and susceptibility to abiotic influences.

7.2 Methodology

7.2.1 Study site

7.2.1.1 Site selection rationale

As the principle that geodiversity underpins biodiversity (Burek, 2001) is at the core of this study, it was decided that the limestone pavement sites selected for microclimate study were also investigated for invertebrate identification. The site selection methodology is provided in greater detail in Subsection 3.3 of the methodology of this thesis.

7.1.1.2 Microclimate data

The five sites selected for invertebrate surveying have been used for extensive microclimate measurement. By accessing both the microclimatic data and the invertebrate sample information, it is possible to hypothesise the interaction of species and their abiotic environment. This type of research has been done routinely in cave management (Ferreira, 2015; Mammola, Piano & Isaia, 2016; Lunghi, Manenti & Ficetola, 2017) and was done by Silvertown when investigating the link between flora and microclimate.

7.1.1.3 Geographical limitation and comparison

The sites selected were situated on The Burren and an area within and surrounding the Yorkshire Dales. The sampling procedure for these sites and site descriptions are detailed in Subsection 3.3. The two Burren limestone pavements were situated within The Burren National Park, which is distinctive and dominated by its karst landscape (Drew, 2001). The habitat is described as rich in flora which is attributable to the wide range of microhabitats and microclimates. These protect the grike species from heat and drought that in normal circumstances test the tolerance of various species present (Heslop-Harrison, 1960). The Yorkshire Dales and bordering areas of Cumbria are a mosaic of high elevation pastures, meadows, grass moorland, upland heathland and blanket peat mire (Bradter et al., 2011). This plethora of habitats contrasts with The Burren, allowing for a comparison of limestone pavements within differing landscape-scale habitats.

Based on the justifications outlined, the following limestone pavements were selected for sampling Holme Park Quarry, Dale Head, High Folds, Fanore and Turlough More.

All sites surveyed in Great Britain had a justification for being categorised under the Willis' Groups, making it possible to compare the findings of this study to those of Willis (2011). The sites selected represented a gradient in the number of floral species present in a pavement community or floral species richness (Magurran, 2013). These ranged from the low species richness, found in Groups 1 to Group 6, which was considerably higher in species richness.

Group 1 (High Folds) was at the lower end of the species richness range, representing the second weakest type of pavement grouping in this criterion after Group 7. Group 3 (Holme Park Quarry) was described as average in species richness, with a high prevalence of negatively impacting flora such as Bracken (*Pteridium aquilinum*) and Gorse (*Ulex europaeus*). The Holme Park Quarry pavement featured in Willis's study and was found to have the equal highest number of species in Group 3. Group 6 (Dale Head) was the most species-rich of the Willis groupings. The Dale Head pavement, in particular, was featured in Willis's study. This pavement had a low number of species for this Group, and a lower number of species than that of Holme Park Quarry. Dale Head was also singled out as being particularly heavily grazed and shown to have signs of "negative" species such as Creeping thistle (*Cirsium arvense*) (Willis, 2011).

7.1.1.4 Site Selection

In studies surveying limestone pavements for invertebrate life, researchers surveyed the entire pavement. In the case of floral and mollusc surveying as part of a Willis' work, the entire pavement required inclusion to gain a holistic impression of the limestone pavement (Willis, 2011). In other surveys of grike invertebrates, the sole purpose of the study was to ascertain the invertebrate presence or absence concerning the physical properties of a limestone pavement (York, 2009). This type of study was not limited by any other factor other than the pavement area. In the current study, the primary concern when sampling invertebrates was that the sample area represented the area of limestone pavement also being used for microclimate sampling.

Limestone pavements are often part of an area, made up of multiple smaller pavements or units of differing size and character (Wilson & Fernández, 2013; Natural England, 2018). Some sites such as Turlough More and Fanore may span tens of square miles. To ensure that the microclimates measured represent the grikes being surveyed for invertebrate fauna, the invertebrate surveys were limited to the pavement section near the grikes used for microclimate data collection. This methodology was based upon that of Dickinson Pearson and Webb (1964) who surveyed vegetation on transects close to the grikes in which microclimatic data were being collected.

On larger pavements, there was no physical limitation to the size of the sample area. Therefore, the permissible size of the sample area was limited to the size of the smallest limestone pavement surveyed, which was High Folds (shown in Figure 7.2.

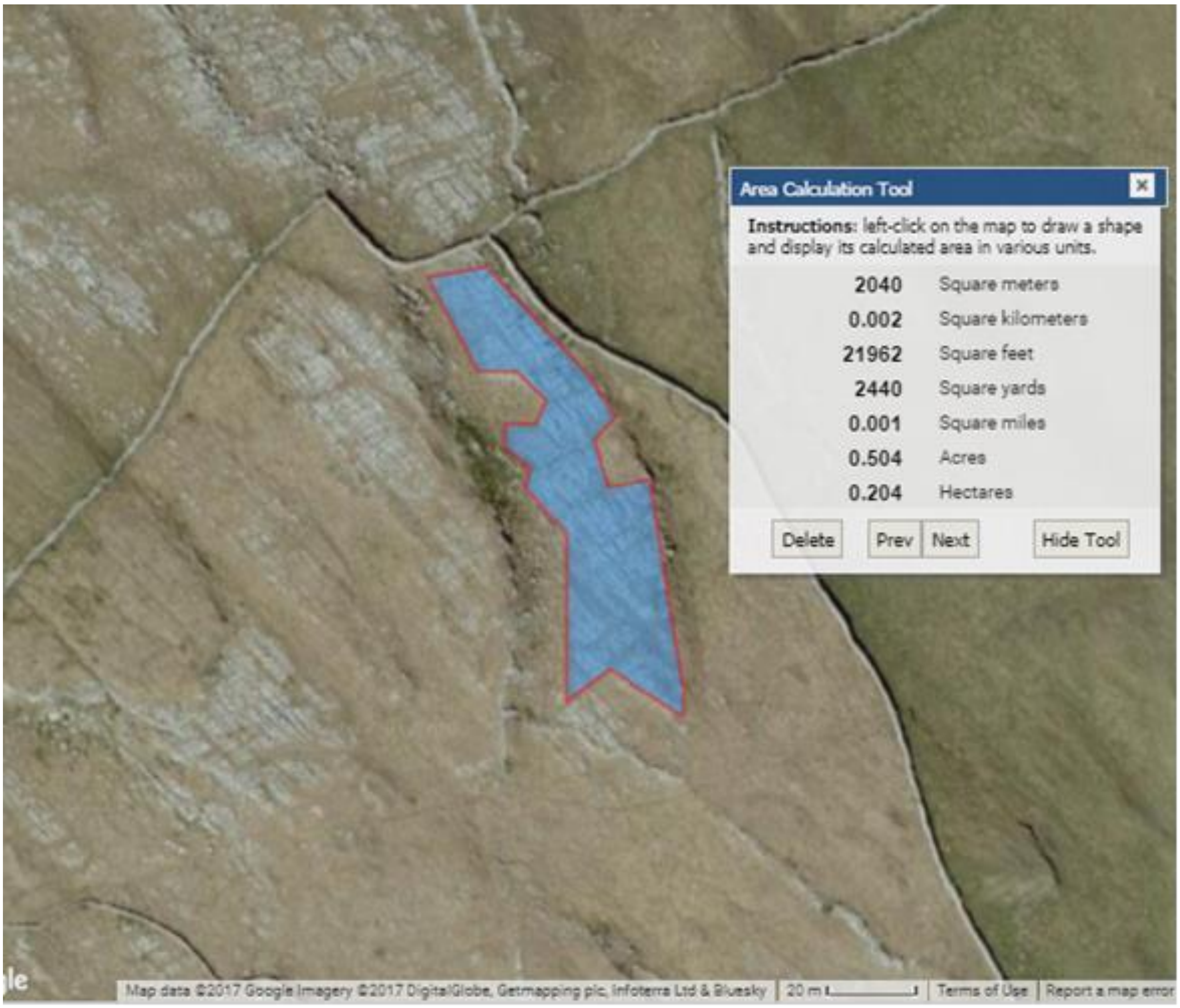


Figure 7.2 Aerial view of High Folds pavement survey section (Yorkshire Dales, UK). (www.gridreferencefinder.com)

This section was separated from the surrounding area by a change in elevation, producing a natural barrier or gap in limestone pavement coverage beyond. The limestone pavement beyond this barrier of elevation received greater exposure to wind and was therefore deemed not of the same microclimate environment as the area sampled. This differentiation in microclimate was based on street canyon literature, which has been observed in other chapters to resemble the microclimate of a grike. In street canyons, the temperature observed at the bottom of a canyon varies in relation to wind-speed (Memon, Leung & Liu, 2010) and it was therefore surmised that the same is true of grikes, making an area of higher elevation and wind exposure unsuitable for the survey. On all other pavements, there were no physical barriers to limit the survey area. A section of pavement was measured, equal in size to the area surveyed on High Folds. This was done in order to provide consistency in samples.

The area surveyed was a 25m radius near the data loggers, producing a 50m diameter circle with an area of 1963.5m2 for surveying.

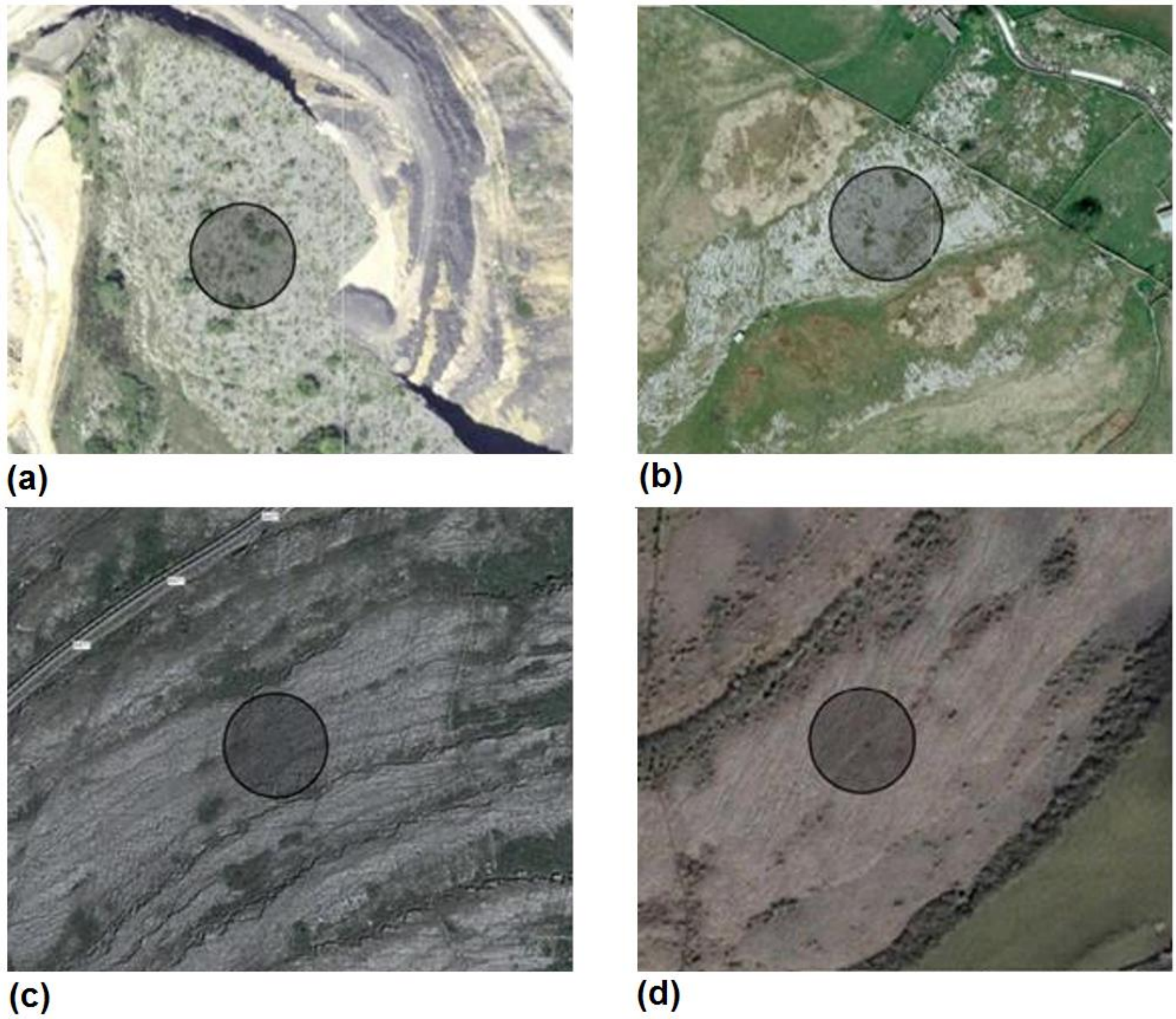


Figure 7.3 Aerial view of limestone pavements and the areas sampled for invertebrate life.

(a) Holme Park Quarry (Cumbria, UK)

(b) Dale Head (Yorkshire Dales, UK)

(c) Fanore (The Burren, Republic of Ireland)

(d) Turlough More (The Burren, Republic of Ireland)

7.1.1.5 Grike Selection

A modified stratified selection methodology, called “gradient directed sampling”, has been used to select grikes for sampling. This sampling methodology was developed on the principle that there is a linkage between physical gradients and biological distribution (Whittaker, 1960, 1967). In a study of vegetation, gradient sampling along the lines of microclimate was found to be more effective than random sampling when the aim is to sample the breadth of invertebrate biodiversity in an area (Pilliod & Arkle, 2013). Sampling along a gradient has also been used when the object of the study is to investigate the impact of microclimate on cave species (Secord & Muller-Parker, 2005; Fontanier & Tobler, 2009). The suitability of this methodology is predicated on the linkage between depth of grike and species distribution demonstrated in flora (Dickinson, Pearson & Webb, 1964; Silvertown, 1982), and the strong graduated increase in microclimatic stability with distance from the surface demonstrated in Chapters Four, Five and Six.

In order to select grikes from an even cross-section of depth, orientation and the pavement area, a satellite image of the pavement was superimposed over an OS Explorer 1:25,000 map in Great Britain and OSi Discover 1:50,000 map in the Republic of Ireland. This map was used to plan multiple transects from north to south, starting at the most easterly point and each separated by five metres. The transects were then repeated in an east to west direction, starting at the most northerly point. When completing a transect across the area, there is a greater probability of encountering grikes which are at 90° to the transect. Transects were completed in two orientations in order to sample an even number of EW and NS orientated grikes. Using two orientations of transect increases the probability of counting the same grike twice. To reduce the chance of double counting grikes and to survey a representative number of grikes, a separation of five metres was placed between transects. Once in the field the transects were walked aided by a GPS to match the mapped transect coordinates to the site. Every grike bisected by the transect was labelled and be measured for depth using a two-metre ruler, and for orientation using a compass. The grikes sampled ranged in depth from 0.2 cm to 2m necessitating a two-metre ruler, grikes which were over two metres in depth were discounted from the study due to the limitations of the equipment used for sampling. Once all measurements were taken, grikes were split by their orientation into two groups, NS and EW. The depth of each group of grikes was put in ascending order. The total number of grikes in each group were divided by 15 to give x; grikes were chosen from the ordered lists of grikes at increments of x, to produce a combined list of 30 grikes representative of the pavement. If any data loggers are present on the site, the grikes in which measurements have taken place have also been chosen for sampling. The number of grikes sampled was calculated based upon a previous study by York (2009), who sampled invertebrates using pitfall trapping to collect 600 grike samples. Pitfall trapping though different from vacuum sampling has been shown to collect a comparable number of individual invertebrates in a wooded habitat (Merrett & Snazell, 1983). Based on the mean and standard deviation of invertebrates collected by York (2009) the current study is required to collect 25 samples to have a 95% chance of receiving a relative percentage precision (PRP) of 21% (Sutherland, 2006). The 25 samples prescribed for each site were increased to 30 to allow for an even split between the different orientations of grike. A sample size of 30 is also considered a minimum for ecological studies sampling along a gradient (Schweiger, Steinbauer, Dengler & Beierkuhnlein, 2016).

7.2.2 Data Collection

7.2.2.1 Prior considerations

The prior considerations for working on limestone pavements and the precautions taken to limit disturbance are documented in Subsections 4.2.2.1 and 4.2.3.3 in Chapter Four. In addition to the actions taken in earlier fieldwork, further precautions were taken in this area of research because it included the removal of invertebrates from a protected limestone pavement site. Further methodological approval and authorisation were gained from the relevant statutory agencies as recommended by DEFRA (Department for Environment, Food and Rural Affairs, 2015). Permissions from Natural England and the Irish National Parks & Wildlife Service were gained before the study. Ethical approval was not required for this study because none of the invertebrates expected to be sampled is protected by the Animals (Scientific Procedures) Act 1986 or Animal Welfare Act 2006 however more recent developments in the ethics surrounding invertebrate capture identify ways to improve methodologies (Drinkwater, Robinson & Hart, 2019). In order to ensure a high standard of ethical conduct was adhered to, the methodology for this chapter was discussed with the relevant statutory agencies and the PhD supervisory team. Based on these discussions, actions were taken to minimise animal suffering by collecting the minimum number of samples per site, euthanising invertebrates as soon as possible after capture and retaining samples after surveying so that other researchers need not collect more samples. This action was taken in order to ensure that the study was conducted with the least disturbance possible in the circumstances.

7.2.2.2 Invertebrates considered

As has been discussed previously, there is a range of molluscs and arthropods common to limestone pavement grikes. Amongst these Phyla there are particular groups, from which a wide diversity of species has been found within grikes, making them prospective indicator species for microclimatic impact. Gastropoda, Carabidae and Isopoda were selected to be the focus of this study based on their relative ubiquity and value as indicators of microclimate.

7.2.2.2.1 Gastropoda

Gastropoda is a taxonomic class of snail and slug species. In Britain, there are between 115 and 213 species of terrestrial gastropod, whereas on the island of Ireland, there are 163 (Tilling, 1987; Anderson, 2005). Multiple studies have been conducted investigating the diversity of snails on limestone pavements finding a wide range of species (Cameron, 1978), constituting 12% of invertebrates sampled (York, 2009) and showing that diversity increases with mean grike depth (Nichols, 2009; Norris & Willis, 2010). Some species of snail have also been used as indicators of habitat quality and microclimate in several studies. Douglas, Brown and Pederson (2013) state that micro snails found in forests are indicators of mature woodland as they have limited mobility and a degree of habitat specialisation. It is hypothesised that microclimate may influence micro snail populations alongside anthropogenic disturbance (Douglas, Brown & Pederson, 2013). Snails have also been seen to be indicators of species richness, leaf litter diversity, hydrology and altitude indicating that climate specialisation is a possibility (Saubere et al., 2004; Aubry, Magnin, Bonnet & Preece, 2005; Foeckler, Deichner, Schmidt & Castella, 2006; Gerlach, Samways & Pryke 2013)

7.2.2.2.2 Carabidae

Carabidae is a taxonomic family of ground beetle species with 350 species found in Britain and Ireland (Luff, 2007). Gibert & Deharveng (2002) estimated that the Coleoptera contains 73% of the described ‘troglobitic’ terrestrial insects on the Earth, with Carabidae being the most diverse in some instances (Borges, Serrano & Amorim, 2004). Coleopterans and more specifically Carabidae have also been used as early warning indicators for changes in climate. Ashworth (1996) found fossil evidence that current carabid fauna in a site is different from those adapted to the paleoclimate of the same site 10, 000 years ago. No studies have yet directly targeted the role of diversity of Ground Beetles on limestone pavements, though some have included them in species lists (York, 2009).

7.2.2.2.3 Isopoda

Isopoda is a taxonomic order of which the terrestrial contingent is made up of woodlouse species. In Britain, there are 42 species of terrestrial isopods and more than half as many on the island of Ireland with only 23 species (Anderson, 2005; Biodiversity Maps, 2019a). Though this is one of the primary species groups, associated with limestone (Fussey, 1984) and making up 25% of Invertebrates sampled on limestone pavements (York, 2009), no study of grike fauna has investigated this order specifically. Woodlice have been used in several studies to indicate leaf litter quality, toxins and several metal-based soil contaminants (Zidar et al., 2003; Pedrini-Martha, Sager, Werner & Dallinger, 2012; Mazzei et al., 2013; Kaya et al., 2014). This sensitivity to changes in food has been tested in a microclimatic context, showing that poor quality leaf litter brought on by climate change may be eaten by the larger isopods which then need to compensatory feed in order to cope with the poorer resource (Ott, Rall, & Brose, 2012). Woodlice are also sensitive to changes in aspects of microclimate, such as relative humidity (Warburg, 1987). This handicap is coupled with a limited dispersal capacity making woodlouse prevalence a good indicator of climate changes, and especially relative humidity (Taiti, 2004). This sensitivity was tested by Hassall et al., (2010) finding that *Philoscia muscorum, Oniscus asellus* and *Porcellio scaber* aggregate to create a more favourable microclimate in environments of low relative humidity and high temperature. *Armadillidium vulgare* showed no such clustering behaviour because it is more desiccation resistant.

By demonstrating the prevalence of these taxonomic classifications in limestone pavement grikes, it has been shown that these three groups of invertebrates are likely to constitute most of the samples extracted. Each of these groupings is associated with the grike habitat, and by the presence, absence or quantity of different species within these groupings, different qualities may be deduced about the grike microclimate. As the focus of this study, species within Gastropoda, Carabidae and Isopoda were identified to species level; other groups of invertebrates have been identified to order. This was done to provide focus to this investigation but not ignore other significant findings.

7.2.3 Invertebrate Sampling

Biodiversity surveying must take place under similar weather conditions and season. All the invertebrates in this study were included in this survey because they were sensitive to climate. For this reason, it was important that weather conditions were kept as constant as possible. Surveys were carried out on the limestone pavements in Great Britain between May and June of 2013 and between May and June of 2014 on the pavements in The Republic of Ireland. This period was selected as it fell during one of the most active periods for both woodlice and snails (Warburg, 1987; Barker, 2001). Figure 7.4 and Figure 7.5 show that the temperature of the collecting periods in 2013 and 2014 are slightly warmer and of average rainfall when compared to the surrounding years in both Cumbria and County Clare. The abnormality of temperature may factor into some of the conclusions taken about the prevalence of invertebrate life found on the sites.

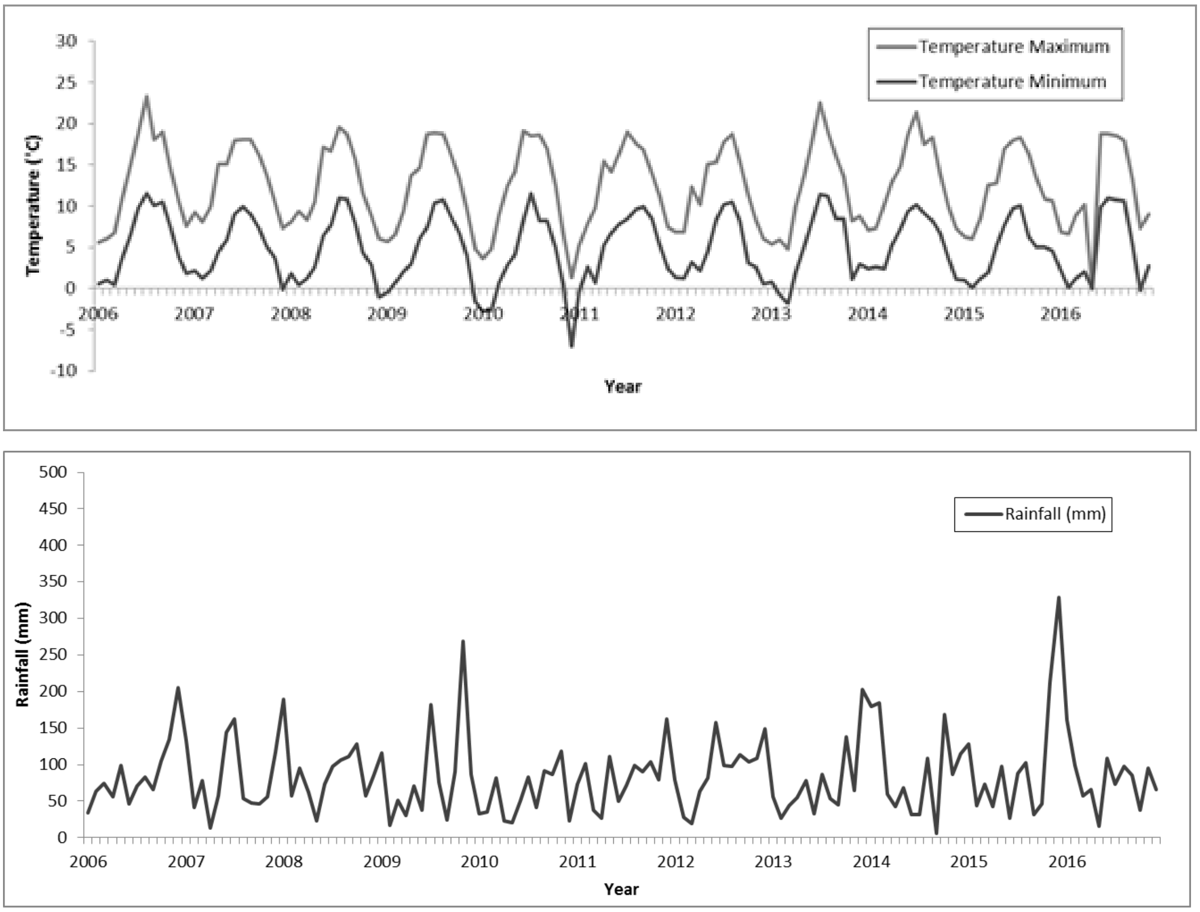


Figure 7.4 Temperature maximum and minimum and rainfall taken from Newton Rigg weather station (South Cumbria, UK) (Met Office, 2017b).

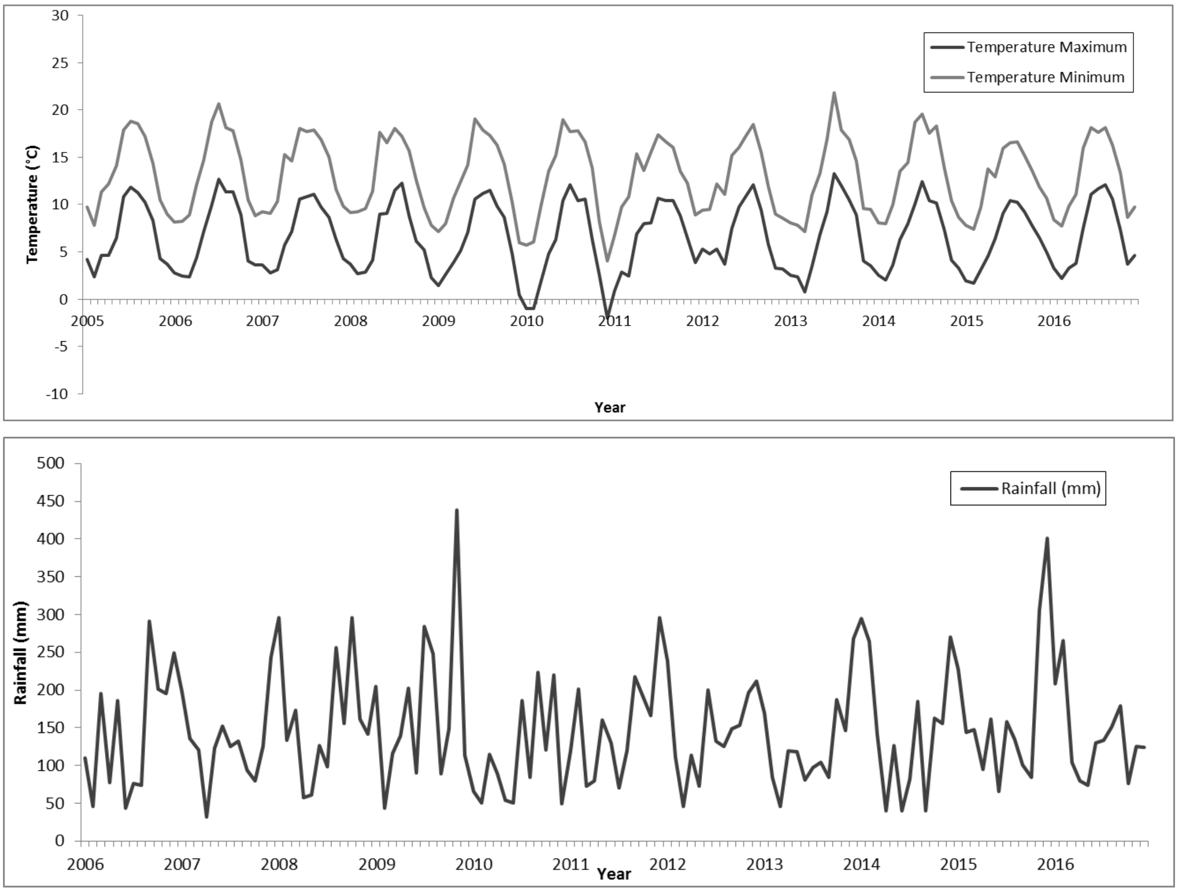


Figure 7.5 Temperature maximum and minimum and rainfall taken from Carran weather station (North County Clare, Republic of Ireland) (Met Éireann, 2018).

In order to standardise conditions, days for the survey have been made as similar as possible. Surveying took place within the hours of daylight and a surveying day was disregarded if rain was forecast. Therefore conditions at night-time and during rainfall have been excluded from the study because they hindered collection and may affect the species collected (Warburg, 1987; Barker, 2001).

Before invertebrates were sampled, each grike surveyed had details about its form and position collected. These included depth, width and orientation. Once this data had been gathered, the invertebrates were sampled using a vacuum sampler.

7.2.3.1 Vacuum sampling

Vacuum sampling has become a standard method for invertebrate capture ever since the introduction of the D-Vac, named after E.J Dietrich in 1959. Since this time comparisons have been made between vacuum sampling, sweep netting and pitfall traps. Some reports show vacuums to be superior (Callahan et al., 1966) although various methods are used for targeting different invertebrate communities (Merrett & Snazell, 1983; Stewart & Wright, 1995, Buffington & Redak 1998; Doxon, Davis & Fuhlendorf, 2011). Vacuum sampling was employed in this study mainly due to the constricted space ruling out netting, and short time frame for sampling ruling out trapping. This limitation may impact the species which are collected. Previously it has been shown that fewer species were collected by vacuum sampling when compared to pitfall trapping and that vacuum sampling had lower successes when sampling larger invertebrates (Merrett & Snazell, 1983).

7.2.3.1.1 Version one

The first vacuum sampler followed a design described by personal communication with Natural England, which had been designed for sampling spiders for re-homing. The vacuum sampler was made from a length of flexible hose connected to a sampling chamber, which in turn was attached to a Garden vacuum. The sampling chamber was made with an unobscured entrance from the hose and an exit to the vacuum covered by a 1mm spaced metal filter mesh to stop invertebrates entering the machinery (Figure 7.6).

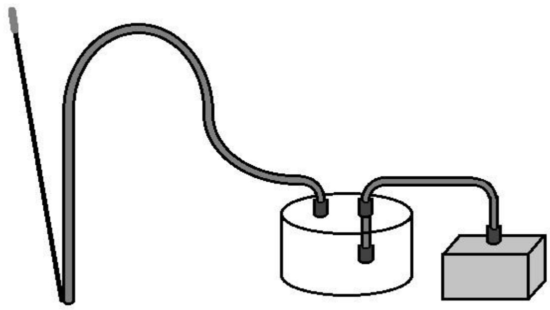


Figure 7.6 Diagram of version one vacuum sampling equipment.

Vacuum sampling has been criticized for not being capable of collecting larger invertebrates (Merrett & Snazell, 1983; Doxon, Davis & Fuhlendorf, 2011). This sampling method was trialled using a range of small Flint Shingle pebbles to replicate the weight of carabid beetles ranging from 0.5g to 1g (Thiele, 2012) to understand the capabilities of the vacuum sampler. The power output was great enough to lift a pebble of 0.9 g but no greater, the lighter samples flew around the sample chamber, and the equipment was very large and cumbersome. It was decided that a second vacuum sampler would be created with a smaller chamber, shorter hose and battery-powered vacuum, as higher power has been shown to improve the capture rate for larger invertebrates (Stewart & Wright, 1995), overcoming the issues raised by Merrett & Snazell (1983).

7.2.3.1.2 Version two

The newer design that was eventually used is described in Figure 7.7. This design was capable of lifting pebbles up to but not exceeding 1.6 g, and there was no such vortex created in the chamber due to the reduced size and more direct air passage. The lighter and less cumbersome design did have a drawback with battery life; however, this was not an issue in this study.

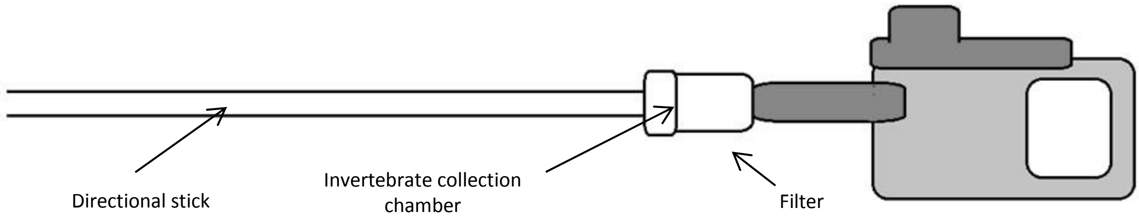


Figure 7.7 Diagram of version two vacuum sampling equipment.

7.2.3.2 Vacuum sample procedure

Vacuuming took place at the bottom of the grike where the hose nozzle was placed firmly into the bottom of the grike, following the example of other studies (Merrett & Snazell, 1983) and moved in a circular motion the diameter of the grike to disturb the detritus at the bottom of the grike. The disturbance was conducted to loosen any invertebrates which may have adhered to rocks or plant matter. Vacuuming took place over a minute and was limited to a one metre stretch of grike. Other studies have cited methods including sampling 11 places within an m^2 quadrat (Merrett & Snazell, 1983) or walking a transect with the end of the hose positioned close to the ground (Doxon, Davis & Fuhlendorf, 2011). There was, however, no precedent set for vacuum sampling in an unobserved environment. This method was chosen because it fits the environment in which surveying took place while incorporating aspects of studies which are effective. The decision to only sample from the bottom of grikes was taken because this part of the grike has been shown to have the most stable microclimate and therefore invertebrates sampled from this area more accurately represent each grike's capacity to provide a stable habitat. To the author's knowledge, the invertebrate life of the bottom of deep grikes has not yet been studied and therefore provides a new area for insights about this habitat.

The time of one minute was chosen due to the limitations of the battery life of the equipment. The Dyson battery of the DC34 can run non-stop for 15 minutes (Dyson, 2013) this allowed for 30 minutes sampling using two batteries.

Once the minute had elapsed, the sample chamber was emptied into a labelled sample pot. Complete samples had all invertebrates removed using a pooter and put into sample jars containing ethanol solution. All Isopod, Gastropod and Carabids were identified to species and all other invertebrates to order level. Sampling and identification were repeated for all grikes identified for this research. Species identification was achieved using “A key to the woodlice of Britain and Ireland by Stephen Hopkin” (2012), “Land snails in Britain and Ireland” (2nd edition) by Robert Cameron (2008) and no Carabid beetles were extracted. However, there were a large number of snails, which proved difficult to identify, and assistance was provided by noted conchologist Adrian Norris, who was able to provide expert guidance.

7.2.4 Analysis

The analysis of sampled invertebrates was conducted in order to isolate the influence of limestone pavement site, grike depth and grike orientation. In all analysis using one-way ANOVA, Spearman Rho and Mann Whitney U, a statistical significance of 0.05 was used.

Analysis of the role of the limestone pavement site was achieved through descriptive statistics from each site, Principal component analysis and an analysis of species diversity using Species Richness and Shannon Index as appropriate for the site. The statistical significance of these differences was tested using one-way ANOVA post-hoc Tukey tests.

The influence of depth on the number of invertebrates and number of species were described through boxplots. The influence of depth on different species capture frequency was investigated through principal component analysis. The correlation between depth and number of invertebrates captured were represented on a boxplot and tested using Spearman Rho. Correlations between species diversity and depth were described using scatter plots. Statistical comparison of different depths was conducted using Spearman Rho test for correlation to identify whether there were significantly greater or fewer numbers of species or total invertebrates sampled at any given depth.

The effect of grike orientation was described through boxplots and descriptive statistics. These showed the effect of orientation on the total number of invertebrates caught, species diversity and capture frequency of each invertebrate species. Statistical analysis was conducted using Mann Whitney U, comparing the two principal orientations collected as part of this study.

Cluster analysis was considered and conducted using the K-means method using the “cluster” library in r. Clustering was conducted to identify if species or sites shared common properties with regard to the number of individual invertebrates captured, the number of species or the depths at which they were captured. All clusters conducted were either inconclusive or displayed conclusions more effectively displayed through other means.

7.2.4.1 Species diversity testing

After researching the topic of diversity indices and their appropriateness for different data (Hill, 1973; Morris et al., 2014), the following indices have been used:

7.2.4.1.1 Species Richness

This simple measure of species identified in a habitat is suited to when the rarer species indicate the difference between habitats, or there is a little variation in numbers of different species (Morris et al., 2014). In this measure, high species richness indicates higher diversity (Whittaker, 1972)

7.2.4.1.2 Shannon index

The Shannon index is derived from the formula in Table 7.1 (Shannon, 1948). This is similar to the Simpson index, containing many of the same components; however, the Shannon index gives more equal importance to both rare and common species (Morris et al., 2014). Typical values fall between 1.5 and 3.5 and are typically narrowly constrained (Magurran, 2013); this number increases as both diversity and evenness increases.

Table 7.1 Equations used to calculate species richness and Shannon index.

Species Richness	Shannon index	Variables
$D = \frac{\sum n(n-1)}{N(N-1)}$	$-\sum_{i=1}^{s} \frac{n_i}{N} In \frac{n_i}{N}$	*n* = number individuals of one particular species *N* = The total number of individuals found *In* = The natural log *s* = number of Species

7.3 Results

7.3.1 Site

Each site contained species characteristic of a limestone pavement made up largely of snails and woodlice, there were however some differences between each site

7.3.1.1 Site comparison

It can be seen from the qualitative descriptions of each site (Appendix 3) that they each possess similarities in the species which may be found within the grikes. A comparison of the sites was conducted in order to identify what differences and similarities they have and whether pavement Groups possess similarities.

7.3.1.1.1 Number of invertebrates

As can be observed in Figure 7.8, Turlough More has more invertebrates collected when compared to the other sites.

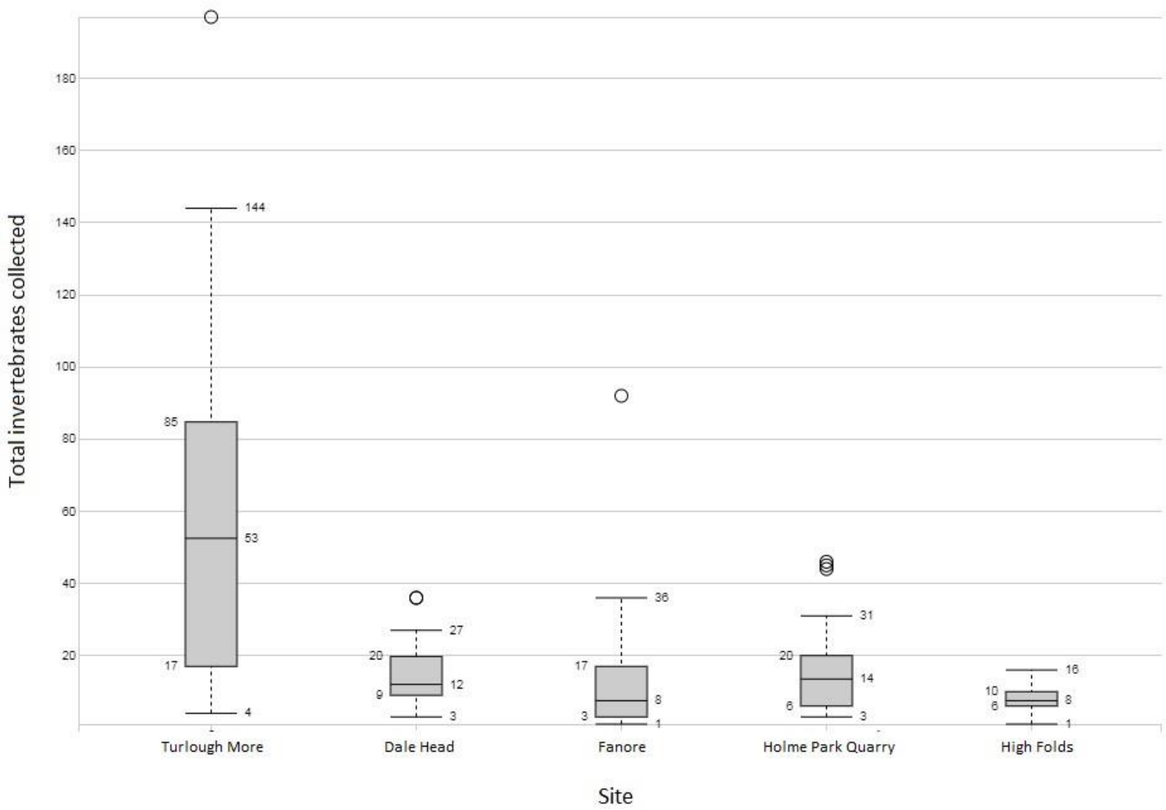


Figure 7.8 A comparison of the total number of invertebrates found in each sample per each site.

When analysed with one-way ANOVA, it was shown that the difference between sites was significant ($F(4,145) = 23.12$, $p < 0.05$) and that in a post-hoc Tukey test, Turlough More was shown to be significantly different to all other sites. Under this ANOVA, no sites other than Turlough More produced samples of invertebrate that were significantly different in number from the other sites. A second ANOVA was conducted excluding Turlough More in order to identify any further differences present between the four remaining sites which may have been masked by the extremely large sample quantities from Turlough More. The results of this second ANOVA test show that none of the four remaining sites is significantly different, and the Post-hoc Tukey test also shows no significant difference between any of the individual sites.

7.3.1.1.2 Number of Species

When comparing the number of species found on each site, Dale Head appears to have the greatest number, and Fanore has the least.

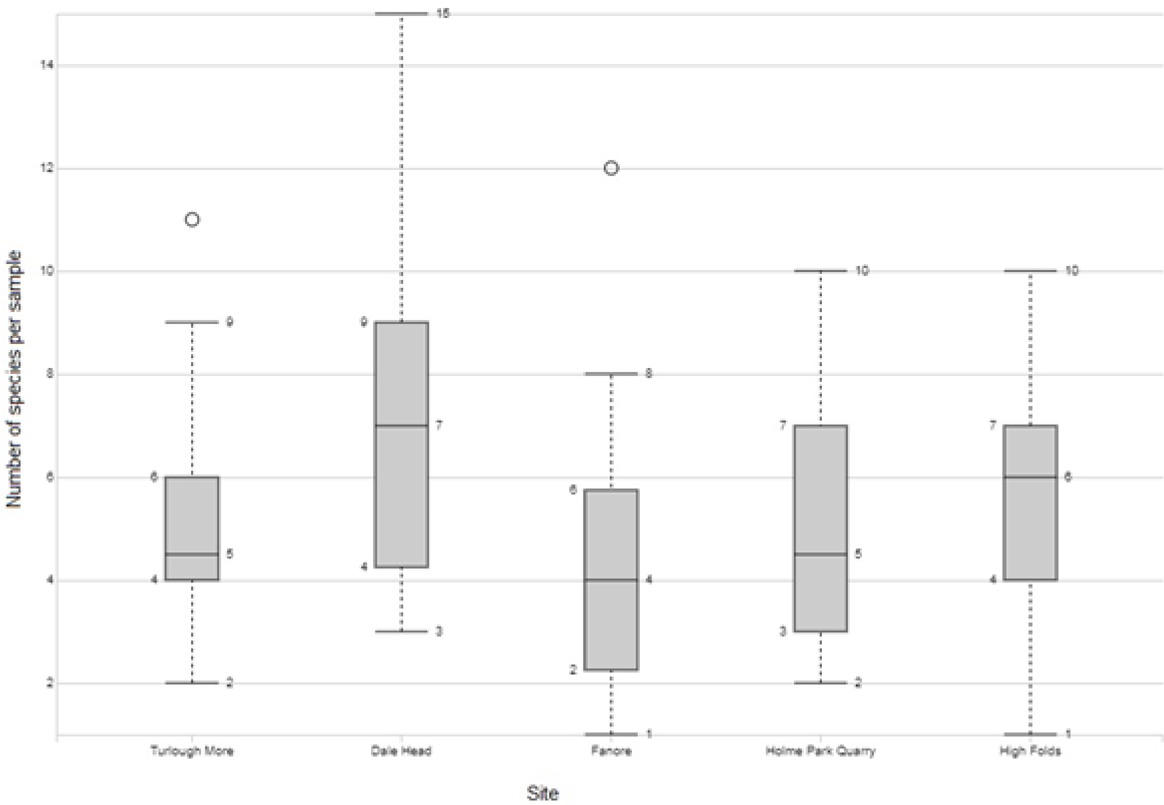


Figure 7.9 A comparison of the total number of species found on each site.

A one-way ANOVA analysis has shown that there is a significant difference in the number of species collected on each site ($F_{(4,145)}$ 6.5616, $p < 0.05$). A post-hoc Tukey test shows that Dale Head has a significantly different median number of species compared to Fanore ($p = 0.001$), Holme Park Quarry ($p = 0.028$) and Turlough More ($p = 0.024$). Dale Head was not significantly different to High Folds, which is from a different Group but is geographically closest to Dale Head. The only other significant difference in the median number of species was between Fanore and High Folds ($p = 0.031$).

<u>7.3.1.2 Principal Component Analysis (PCA) of site and species</u>

A PCA was conducted to identify whether there are any differences or commonalities between the different sites used for surveying. By doing this, it was possible to identify whether there are any distinct groupings of limestone pavement sites and which species drive these groups. This PCA was done using the species which occurred in at least 28 of the 30 samples for each site. Species with a high number of zeros in the data set were removed as this can skew the results of principal component analysis (Hadley & Garrett, 2017).

A set of 15 species which were common to each pavement were plotted against the first two principal components of the relationship between site and species, which explained 99.78% of the variance in the data. Figure 7.10 shows that the two most common species, *Punctum pygmaeum* (SP3) and *Pyramidula pusilla* (SP4) account for a very large amount of the variance between the different limestone pavements. Factor loadings for the 1st component show that *P. pusilla* has a loading factor of -0.89 and *P. pygmaeum* has a loading factor of -0.45. This can be observed to strongly influence the far left position of Turlough More, which contains extremely high numbers of both species. The 2nd component divides those sites with only high numbers of *P.pygmaeum* (Holme Park Quarry) from those with high numbers of both *P.pygmaeum* and *P .pusilla* (Turlough More and Fanore) by loading factors by 0.84 for *P.pygmaeum* and -0.42 for *P. pusilla.*

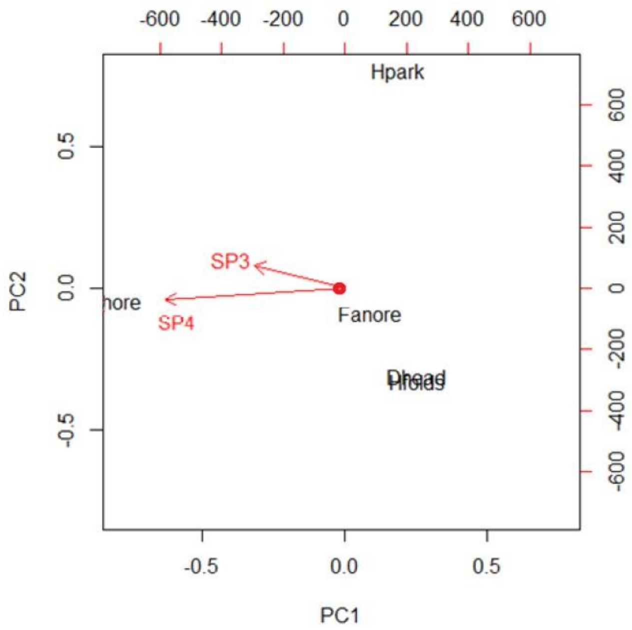


Figure 7.10 Bi-plot depicting the 15 most commonly recorded species plotted against the five limestone pavements studied (black). The species with the greatest influence (red) upon the two principal components (providing a loading factor of 0.1 or greater) are *Punctum pygmaeum* (SP3) and *Pyramidula pusilla* (SP4).

This PCA is dominated by the extremely high number of these two species found on the Turlough More site. This dominance hides any further interpretation from the bi-plot. In order to make further interpretations, the PCA was carried out twice more. Once excluding the two most common species, and once excluding Turlough More, in this way further interpretation can be made.

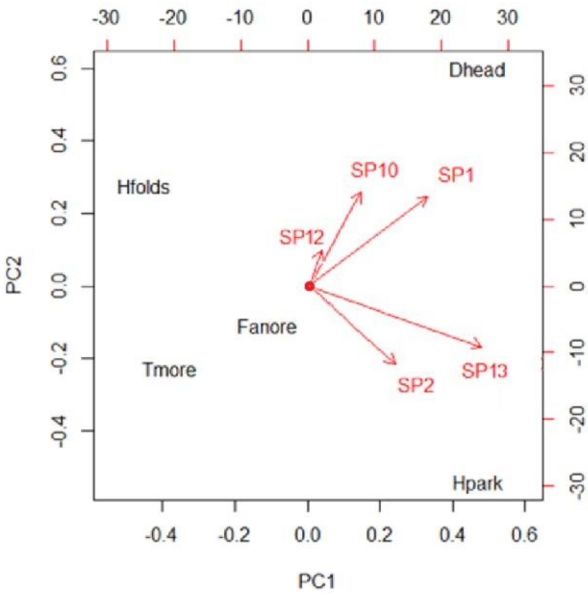


Figure 7.11 Bi-plot depicting the 13 most commonly recorded species after the removal of the two most common species plotted against the five limestone pavements studied (black). The species with the greatest influence (red) upon the two principal components (providing a loading factor of 0.1 or greater) are *Discus rotundatus* (SP1), *Lucilla singleyana* (SP2), *Carychium tridentatum (*SP10), *Pupilla muscorum* (SP12) and *Lauria cylindracea* (SP13). Loading factors are available in Table 7.2.

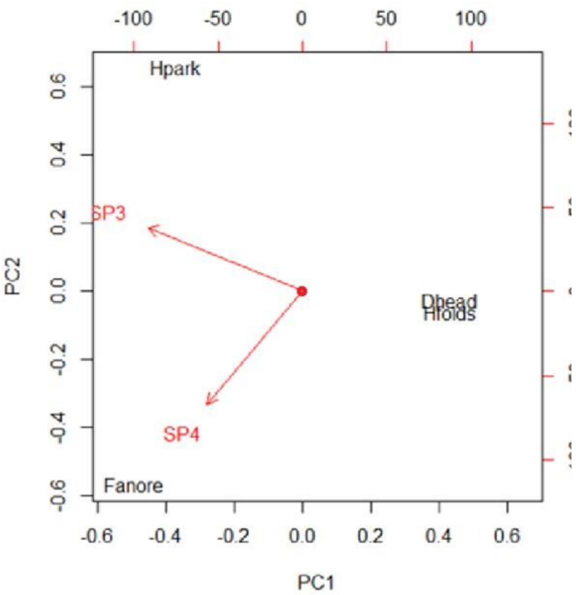


Figure 7.12 Bi-plot depicting the 15 most commonly recorded species plotted against the four limestone pavements studied excluding Turlough More (black). The species with the greatest influence (red) upon the two principal components (providing a loading factor of 0.1 or greater) are *Punctum pygmaeum* (SP3) and *Pyramidula pusilla* (SP4). Loading factors are available in Table 7.2.

Table 7.2 Loading of the most influential species analysed by PCA to distinguish the principal components of the different limestone pavements.

	Two most common species removed		Turlough More removed	
Species	1st component	2nd component	1st component	2nd component
Discus rotundatus	0.49	0.49		
Lucilla singleyana	0.36	-0.43		
Punctum pygmaeum			-0.83	0.47
Pyramidula pusilla			-0.51	-0.83
Carychium tridentatum	0.22	0.51		
Pupilla muscorum	0.06	0.21		
Lauria cylindracea	0.72	-0.33		

By removing Turlough More, the first two principal components now explain 95.56% of the variance in the data, and by removing the two most common species, the first two principal components now explain 96.04% of the variance in the data.

By including *Punctum pygmaeum* (SP3) and *Pyramidula pusilla* (SP4) and removing Turlough More (Figure 7.12), it can be observed that these more common species drive most of the difference between the sites. The Yorkshire sites, High Folds and Dale Head are united by their relative lack of these two species, and Fanore and Holme Park Quarry are in separate groups driven by *Pyramidula pusilla* presence in Fanore and absence in Holme Park Quarry.

With the two most common species removed (Figure 7.11), it is possible to observe the smaller differences in sites driven by species other than *Punctum pygmaeum* and *Pyramidula pusilla*. Holme Park Quarry is distinguished from other sites by a high number of *Lauria cylindracea* (SP13) (43) and that Dale Head is distinguished by high numbers of *Carychium tridentatum* (SP10) (24) and *Discus rotundatus* (SP1) (35). High Folds site does not appear to be distinguished by a high number of any particular species but by an absence or a low number of most of the species more common to the limestone pavement grikes, such as *Lauria cylindracea* (2) and *Lucilla singleyana* (SP2) (0). The most similar pavements are those in the Republic of Ireland,
Turlough More and Fanore which are geographically close and contain no *Lucilla singleyana* or *Pupilla muscorum* (SP12), and only 13 *Discus rotundatus* in the Fanore site, distinguishing it from Turlough More. The biogeography of these species is discussed in greater detail in the discussion of this chapter.

Based on this PCA of species numbers on sites, it would appear from the close proximity of the sites in the Republic of Ireland and those in the Yorkshire Dales that geographic location has a larger influence than the pavement Groups created by Willis (2011).

7.3.1.3 Species diversity by site

Samples were tested using species richness and Shannon index to identify any differences in species diversity within or between pavement Groups by looking at each site individually. Figure 7.13 shows how diverse the species of caught invertebrates are for each of the limestone pavements.

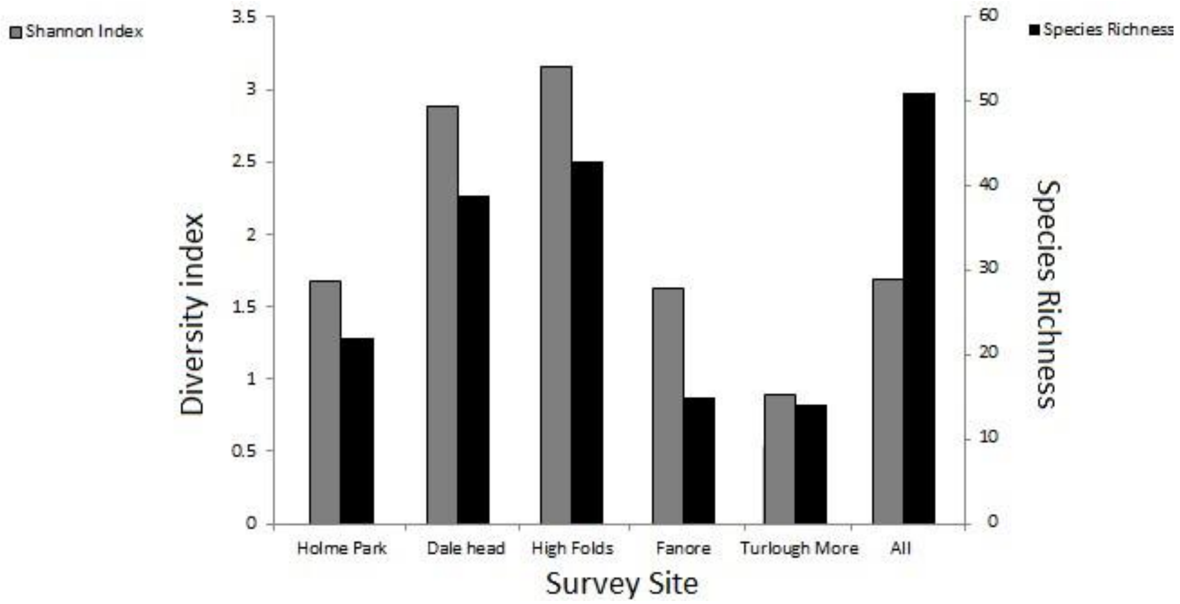


Figure 7.13 Species diversity by limestone pavement site using Shannon Diversity index (left) and Species Richness (right).

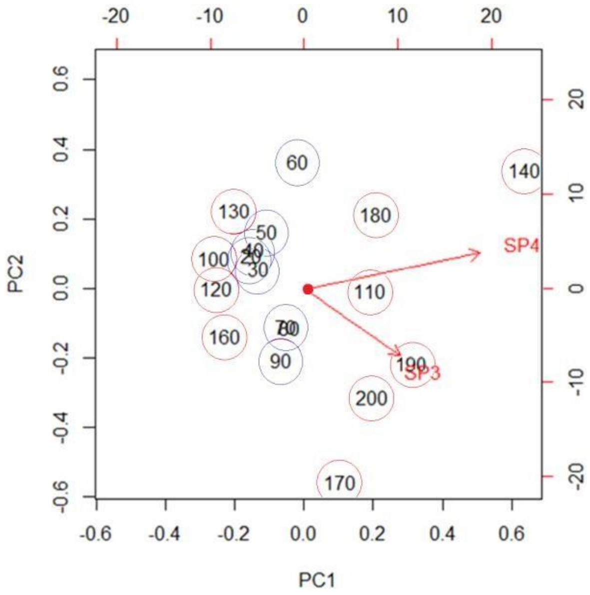
Willis' research indicates that floristic species richness is highest at Dale Head (Group 6) and lowest of High Folds (Group 1) (Willis, 2011); however, these sites are comparable in faunal species richness. Instead, these results further highlight the difference between geographic locations. The most Diverse sites are Dale Head and High Folds which are both located in Yorkshire, whereas the Irish pavements found in Fanore and Turlough More are least diverse.

7.3.2 Depth

7.3.2.1 Principal Component analysis of depth and species

PCA was conducted to identify which depths are distinctly analogous or different. By doing this, it has been possible to identify if the groupings of analogous grike depths established from invertebrate surveying are comparable to the grike depth groupings generated by the microclimate observation in Chapter Four. PCA was conducted with 12 of the most common species in this study. Species which occurred at fewer than half the depths were removed to reduce the sway of zero counts (Hadley & Garrett, 2017).

The first two principal components explain 99.91% of the variance in the data. Due to their abundance, *Punctum pygmaeum* (SP3) and *Pyramidula pusilla* (SP4) dominate the distribution of depths in the bi-plot. In order to remove this influence, a second bi-plot was created to illustrate any further interactions. A new PCA was conducted in which the first two principal components explain 66.83% of the variance in the data.



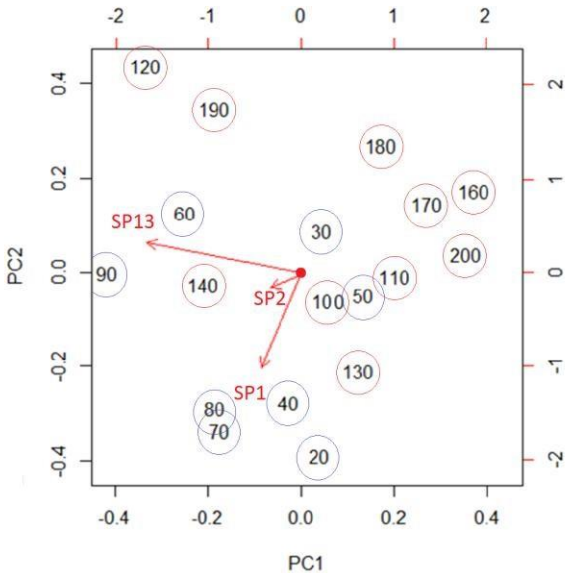


Figure 7.14 Bi-plot depicting the 15 most commonly recorded species plotted against the depth of grike in which species were found (cm) (black). Depths of 100cm and below are ringed with blue and above 100cm are ringed in red. The species with the greatest influence (red) upon the two principal components (providing a loading factor of 0.1 or greater) are *Punctum pygmaeum* (SP3) and *Pyramidula pusilla* (SP4). Loading factors can be found in Table 7.3.

Figure 7.15 Bi-plot depicting the 13 most commonly recorded species after the removal of the two most common species plotted against the depth of grike in which species were found (cm) (black). Depths of 100cm and below are ringed with blue and above 100cm are ringed in red. The species with the greatest influence (red) upon the two principal components (providing a loading factor of 0.1 or greater) are *Discus rotundatus* (SP1), *Lucilla singleyana* (SP2), and *Lauria cylindracea* (SP13). Loading factors can be found in Table 7.3.

Table 7.3 Loading of the most influential species analysed by PCA to distinguish the principal components of the different limestone pavement grike depths.

	All 15 most common species		Two most common species removed	
Species	1st component	2nd component	1st component	2nd component
Discus rotundatus			-0.24	-0.88
Punctum pygmaeum	0.48	-0.88		
Pyramidula pusilla	0.87	0.48		
Lucilla singleyana			-0.21	-0.16
Lauria cylindracea			-0.92	0.28

In Figure 7.14, *Punctum pygmaeum* (SP3) and *Pyramidula pusilla* (SP4) appear to predominate in the deeper grikes illustrated by a left-right split in a grouping of the depths. On the right, there are no depths below 100cm, and most depths are above 150cm. This indicates an influence of depth on invertebrate distribution and most especially in the distribution of the two most common species. The vertical split driven by the 2nd component indicates that *Punctum pygmaeum* is especially common in the deepest grikes as it is found more than *Pyramidula pusilla* in 170, 190 and 200cm deep grikes.

When the two most dominant species are removed (Figure 7.15) the depths of grike fit into three groupings, there is a cluster driven toward the bottom of the bi-plot by *Discus rotundatus* (SP1) which includes several shallower grikes below 100cm. There is a cluster of mid-depth grikes to the left of the bi-plot, in which *Lauria cylindracea* (SP13) is found in high number. There is also a large cluster of deeper grikes to the top right if the bi-plot which all contain lower numbers of species other than *Punctum pygmaeum* and *Pyramidula pusilla,* which dominate the habitat.

7.3.2.2 Comparison of depth

The number of invertebrates collected and the number of species identified were compared graphically and using Spearman's Rho. This was done in order to provide indications of whether depth impacts the number of species or invertebrate population size. By showing this, there may be a greater justification that depth and microclimate influence the number of invertebrates of species in a grike.

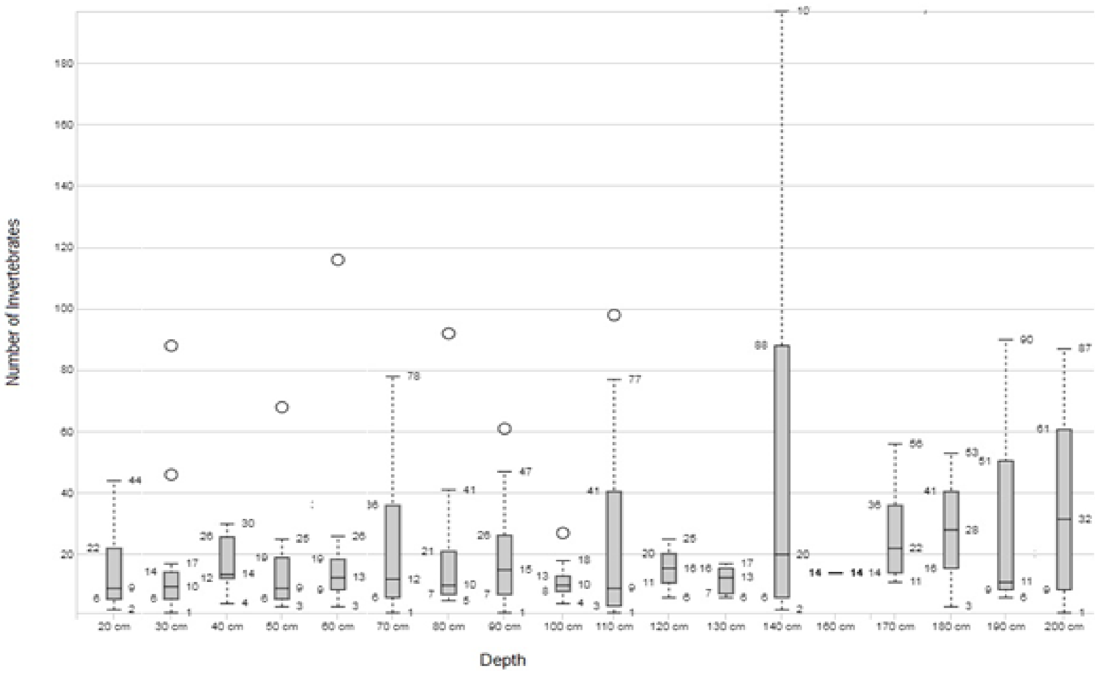


Figure 7.16 Boxplot showing the number of invertebrates collected in each sample within grikes of different depths on all sites studied.

Figure 7.16 shows that there is a slight increase in the spread and median of invertebrates collected from grikes below 130cm compared to shallower grikes and the shallowest grikes above 60cm have both low invertebrate capture numbers, and low median and variance in capture numbers. The total number of invertebrates per species was analysed using Spearman Rho analysis to show that there was a significant correlation between the numbers of invertebrates collected in each depth of grike ($r_s = 0.270$, $p < 0.05$).

The number of species found in each depth was then represented in Figure 7.17 and analysed using Spearman's Rho. Both show that there was no significant difference in the number of different species found at the different depths of grike ($r_s = -0.008$, $p = 0.928$).

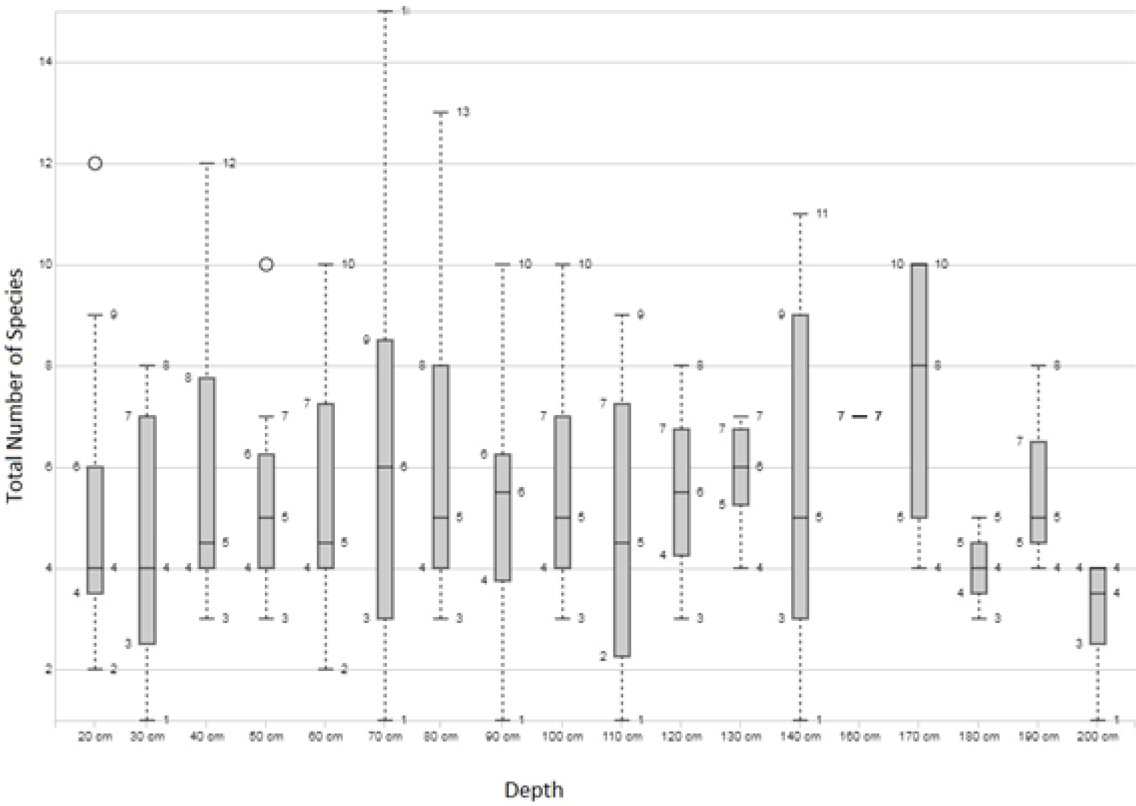


Figure 7.17 Boxplot showing the number of species found in each sample within grikes of different depths for all sites under study.

7.3.2.3 Correlation between depth and invertebrates counted

Further analysis was conducted to establish whether there was a correlation between the number of invertebrates caught and the depth of the grike.

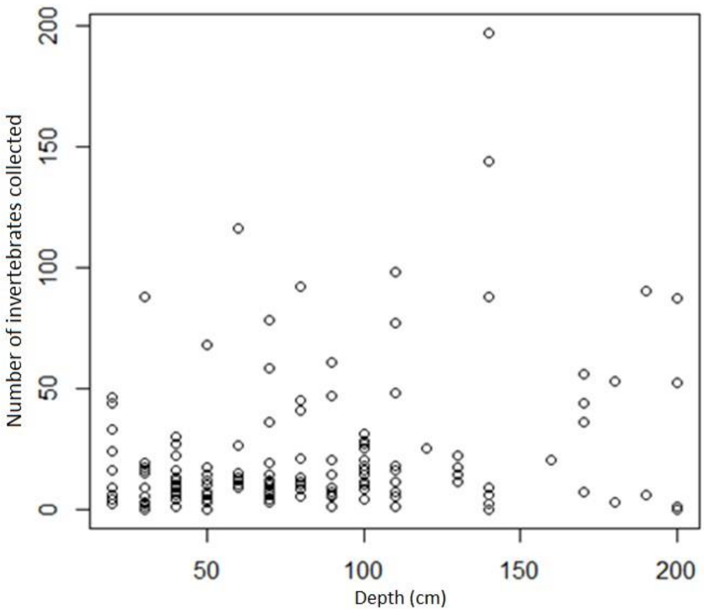


Figure 7.18 Number of individual invertebrates counted from each sample, plotted against the depth of the sample.

Figure 7.18 shows the number of individual invertebrates counted from each sample plotted against the depth of the sample. This plot shows a slight positive correlation between depth and invertebrates collected. The correlation was then tested statistically using the Spearman Rho test for correlation identifying a significant correlation ($r_s = 0.214$, $p < 0.05$).

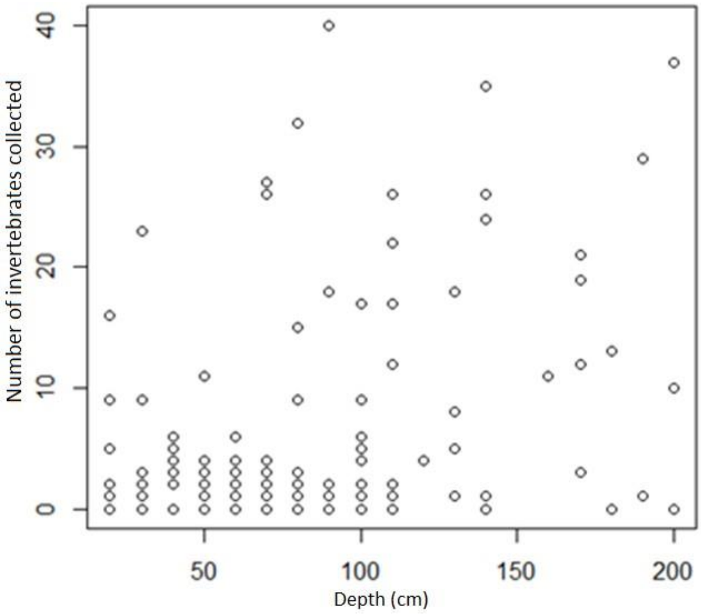


Figure 7.19 Number of individual invertebrates counted from the species Punctum pygmaeum plotted against the depth of the sample.

Several further plots were then carried out using the key species previously mentioned. Of the individual species tested, only *Punctum pygmaeum* was shown to be significantly correlated with depth ($r_s = 0.256$, $p < 0.05$).

7.3.2.4 Species diversity and depth

Previously in this chapter, it has been shown that there is a significant correlation between the number of invertebrates per collection and depth. Figure 7.20 and Figure 7.21 show that while the mean number of invertebrates counted in each grike tends to increase with depth, the mean number of species counted slightly decreases with depth.

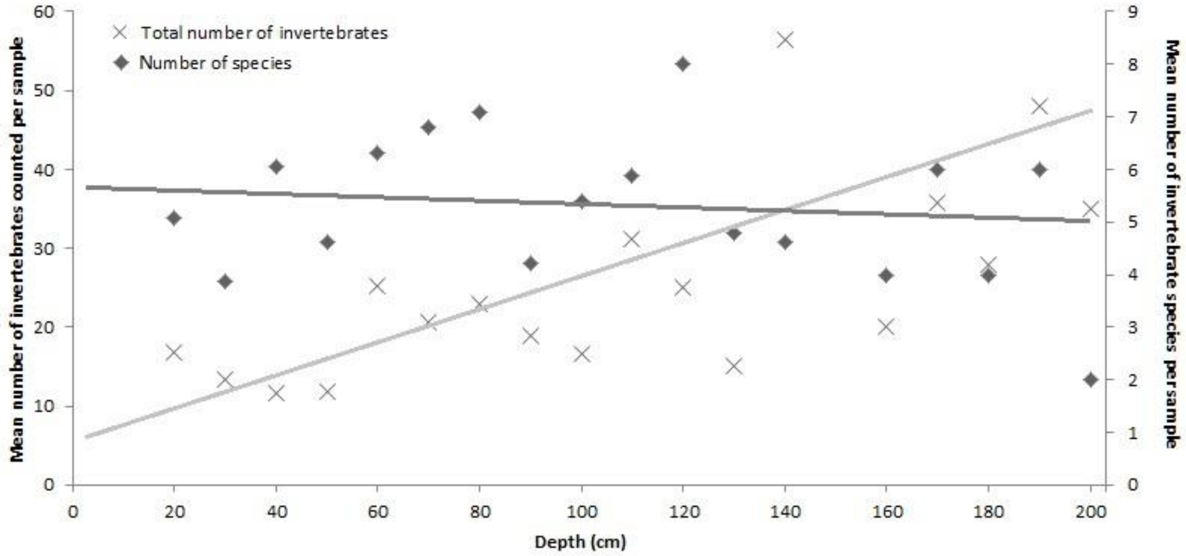


Figure 7.20 Median number of species and invertebrates counted in each sample at different depths in limestone pavement grikes.

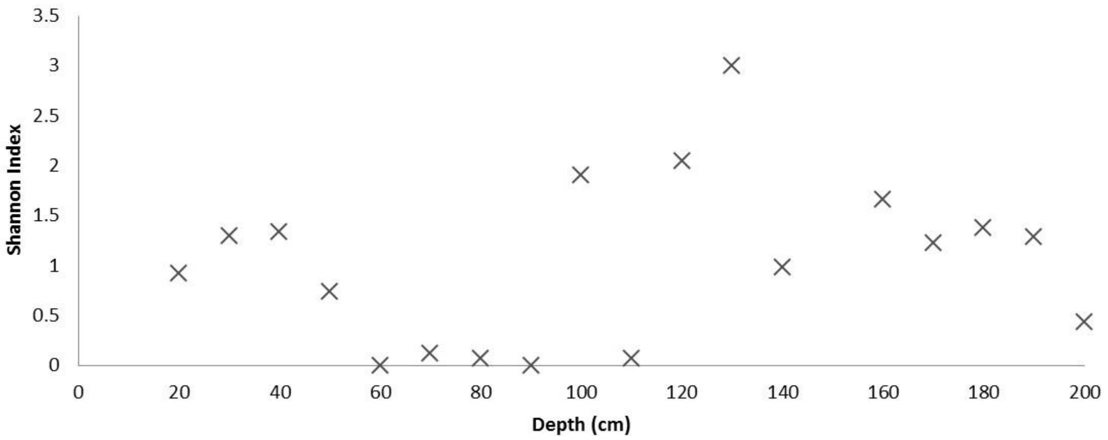


Figure 7.21 Shannon diversity index calculated for different depths in limestone pavement grikes.

If one observes the number of species counted at each depth, there appears to be little difference as depth increases. However, species diversity indices show three distinct zones in the grike with differing species diversity. The species diversity is moderate from 20cm to 50cm into the grike, relative to other depths. The diversity of species then decreases beyond 50cm until 100cm where it increases once again to higher levels than anywhere else in the grike before reducing again.

7.3.3 Orientation

Within this study, the orientations selected for analysis lie on the cardinal compass directions and on one site 45° to the cardinal compass directions. High Folds is the only site to contain grikes which did not lie on cardinal compass directions and has been shown to have significantly different numbers of species within its grikes compared to some other sites. So that only orientation is being analysed, and so that the influence of different sites does not affect the results, High Folds has been removed from the analysis of orientation. The average depth of grike by orientation was roughly equal (84.21 cm in EW grikes and 84.91 cm in NS grikes), ruling out depth as a compounding influence in this analysis. This means that only NS and EW grikes are compared in the following subsection.

7.3.3.1 Comparison of orientation

Figure 7.22 shows that there are a marginally greater number of invertebrates caught in the EW (Median = 16) grike when compared to the NS grike (Median = 12). However, this difference was not significant when tested using a Mann Whitney U test (U = 1502.5, p = 0.32218).

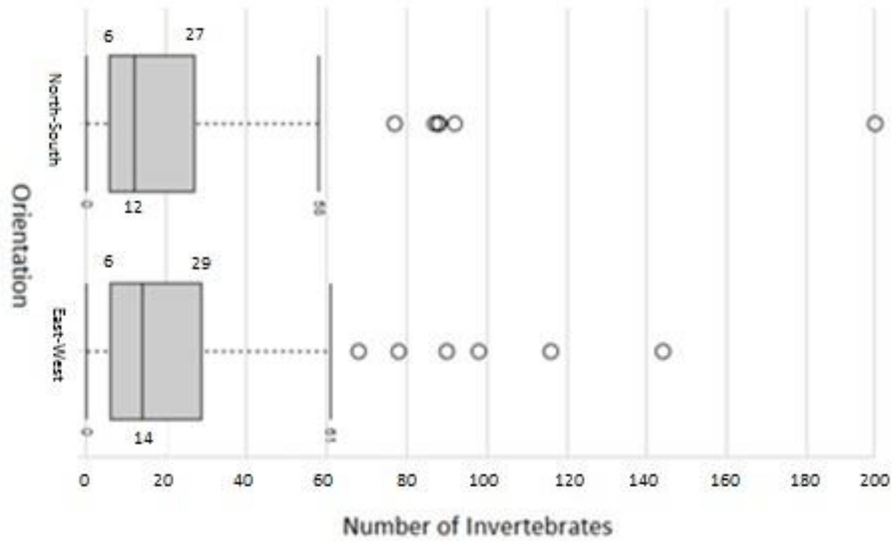


Figure 7.22 Boxplot comparing the number of invertebrates per sample between the two primary grike orientations.

Each species was then tested separately to identify if any species of mollusc or isopod was found in significantly greater number in the NS or EW grikes. When tested using Mann Whitney U, it was found that no species were found in significantly greater numbers in one particular grike orientation; however, some were found exclusively in one grike orientation (Table 7.4).

Table 7.4 Species found only in NS or EW grikes.

North-South (NS)	East-West (EW)
Zenobiella subrufescens	*Folsoma Brevicauda*
	Vitrina pellucida
	Oxychils alliarus
	Cochlicopa cf. lubricella
	Columella edentula
	Balea heydeni
	Porcello scaber

The number of species collected in each orientation of grike was compared in Figure 7.23, which shows that there is a greater number and spread of species caught in the EW grike. A Mann Whitney U test indicated that the while the number of species identified from EW grikes were larger (Median = 5) than in the NS grikes (Median = 4) the difference was not significant (U= 1475.5, p = 0.4).

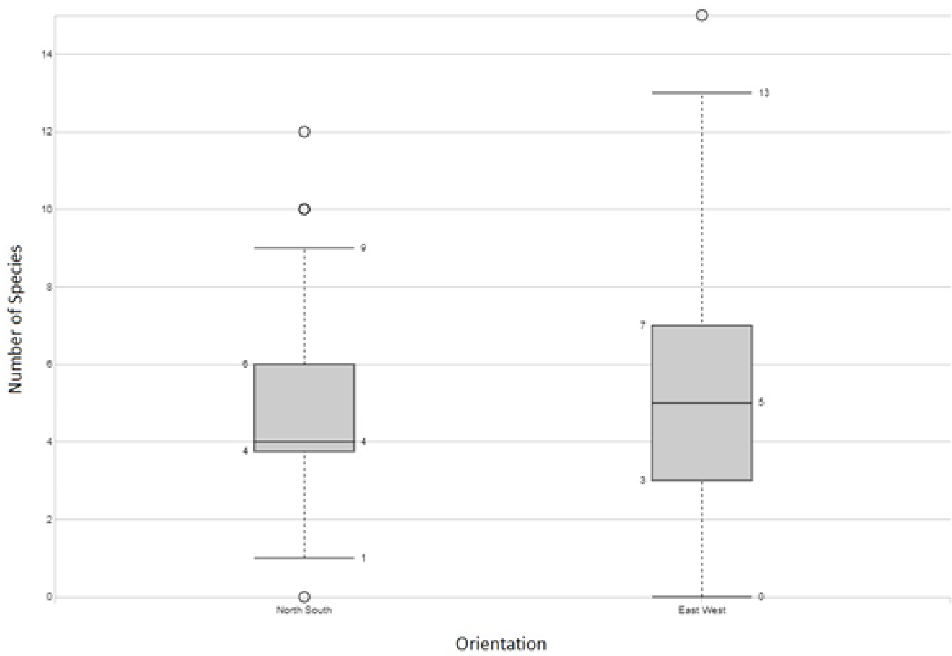


Figure 7.23 Boxplot comparing the number of species per sample between the two primary grike orientations.

The EW grike has been shown to have a higher number of invertebrates and species, and contains more species not found in the NS grike; however, this difference is not statistically significant.

7.4 Discussion

7.4.1 Species and groupings found on all sites

In this survey, three taxonomic classifications of invertebrate were selected for species identification. Of these only Mollusca and Isopoda were found to be present within the grikes studied and species of Mollusca were more common in grikes than Isopoda species. All species found within the grikes of this study are detailed in Appendix Four along with distribution, habitat preference and conservation status. The Isopoda found in this study are both largely saprophagous and digest plant matter externally (Hopkin, 2012), though *Armadillidium vulgare* has a more diverse diet. This means that both species of Isopoda rely upon plant matter entering the grike. All sites studied in this survey are considered open pavements, which mean that there is little vegetation from which to source leaves, whereas other studies sampled from a variety of both wooded and open pavements (Fussey, 1984; York, 2009). Molluscs may not require as ready a source of plant matter in order to thrive. For example, on Oland in Sweden lichen-feeding snails (*Chondrina clienta*) have been hypothesised to graze the cyanobacteria on the clint during the night (Fröberg, Stoll, Baur & Baur, 2011). This behaviour has not been observed in Great Britain or Ireland however this feature warrants further study, as different cyanobacteria are cropped by different snail species (Baur, Baur & Fröberg, 1994) and the characteristic grike lip whitening found in Oland has also been observed in Great Britain (Willis, 2011)

The mollusc found most commonly within this study is *Punctum pygmaeum,* which can be found very widely in Great Britain (Phillipson, 1983) and Ireland as can be seen in Figure 7.24.

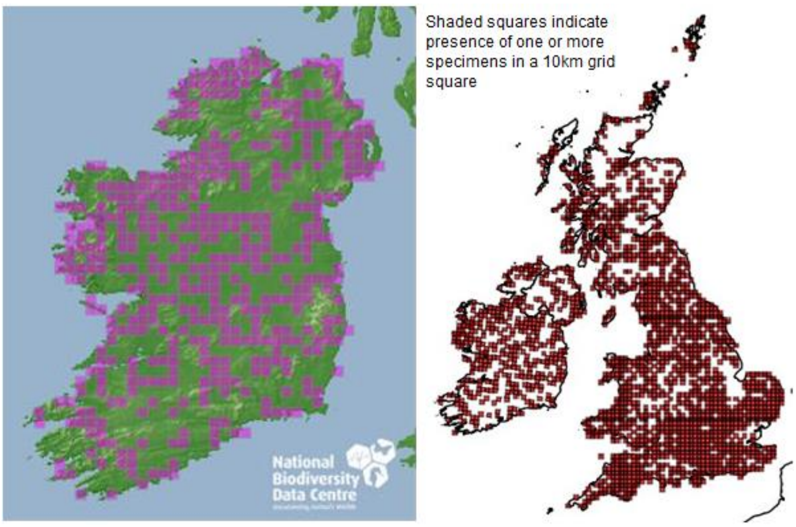


Figure 7.24 Punctum pygmaeum prevalence in Great Britain and Ireland (Biodiversity Ireland, 2017; NBN Gateway, 2017).

P. pygmaeum was found in high numbers in all pavements which were part of this study. This species has been found in abundance in several locations and appears to find a niche in whatever habitat it is found (Kappes, 2005). *P. pygmaeum* are frequently found in habitats with greater vegetative cover when compared to grassland habitats (Chappell, Ainsworth, Cameron & Redfern, 1971; Kappes, Topp, Zach & Kulfan, 2006) but has little preference for the type of vegetation used (Koralewska-Batura, Bloszyk & Napierala, 2006).

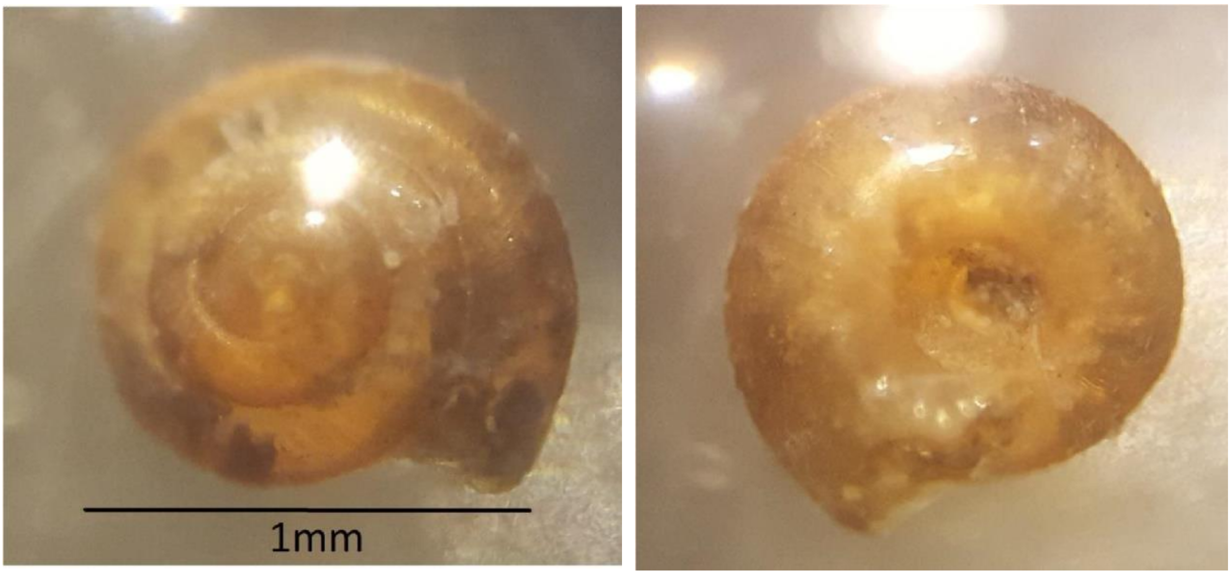


Figure 7.25 Punctum pygmaeum shell, sampled from the Turlough More limestone pavement (The Burren, Republic of Ireland).

It is unclear why this species was found in greater number than any other, as there is evidence to indicate that *P. pygmaeum* may prefer other environments to that of a limestone pavement. In one of the earliest studies of grike fauna, Cameron (1978) describes the abundance of *P. pygmaeum* being higher in bog and mire habitats in the Malham area when compared to the limestone pavements they surveyed. As a generalist, *P. pygmaeum* can adapt too many environments, and if surveyed, it may be found to be in higher still abundance in the area surrounding the limestone pavements surveyed in this study. Alternatively, the limestone pavements in Malham studied by Cameron (1978) may not have been suited to *P.pygmaeum* because of the relative lack of grike depth, as appears to have been the case in this study when comparing *P.pygmaeum* frequency in the High Folds site (near to Malham) to other sites.
The prevalence of *P.pygmaeum* in this study may have been in part due to the method of collection. This species is often overlooked in surveys of habitat because of its size (Cameron & Morgan-Huws, 1975; Cameron, Down & Pannett, 1980; Albano, 2014); however in this study, a vacuum sampler is more likely to collect smaller species as opposed to larger species (Merrett & Snazell, 1983).

Carabidae were absent from any grike in this study, whereas previous pitfall surveys of limestone pavement fauna have been shown that beetles occur in grikes, but to a lesser frequency than molluscs and isopods (York, 2009). The equipment used to survey was modified specifically to increase the possibility of capturing the carabid beetles known to reside within grikes in North Wales; however, it is possible that the modifications did not create enough suction to capture the heavier carabid beetles under the conditions of sampling. It is also possible that carabid beetles occur in pitfall traps in disproportionally high numbers, as has been found when compared to litter washing and funnel extraction (Spence & Niemelä, 1994).

7.4.2 Invertebrates and site

7.4.2.1 Biogeography

7.4.2.1.1 Biogeography between the islands of Ireland and Great Britain

The sites situated in the Republic of Ireland were distinguished through principal component analysis, which identified that Fanore and Turlough More were notable for the absence of *Lucilla singleyana* and *Pupilla muscorum*. In the case of *Lucilla singleyana,* this is unsurprising as this species is not found within the Republic of Ireland and is only a relatively recent introduction to Great Britain (Cameron, 2003). Historically *Pupilla muscorum* has been observed in areas close to both Turlough More and Fanore. However, it is reported to be in decline in the British Isles and endangered in the Republic of Ireland having not been recorded since 2016 (Biodiversity Maps, 2019b). The absence of these species from the sites situated in the Republic of Ireland, therefore, may relate more to the national absence and decline of these species and provides fewer insights into the critical factors present in the grikes which may influence their occurrence.

The sites situated within the Republic of Ireland were further distinguished by having lower species richness and diversity index than sites found in Great Britain. This discrepancy may be due to the smaller number of both gastropod and isopod species occurring in the Republic of Ireland compared to Great Britain.

7.4.2.1.2 Biogeography between sites

A comparison of the invertebrates found per sample identified Turlough More to be significantly different to all other sites when tested using an ANOVA and post-hoc Tukey test. The significantly greater number of invertebrates found here was found to be largely due to the high numbers of

Punctum pygmaeum. As detailed in Subsection 7.4.1, the factors which influence the high presence of this species on limestone pavements are not clear.

The principal component analysis identified that several the sites were distinguished by the relative ubiquity or rarity of certain species. *Lauria cylindracea* was found in relatively large numbers in Holme Park Quarry and low numbers in High Folds when compared to other sites. This species is very common in Britain and Ireland and can be found in woodland, damp grassland, walls, hedges and exposed rocks (Cameron, 2003); however, the presence of broadleaf woodland is a strong indicator for *Lauria cylindrace.* The preference for woodland may explain the higher occurrence of this species in Holme Park Quarry, as the site contains several beech, oak and ash trees in and around the limestone pavement (Allen, 2017).

Carychium tridentatum was more commonly found on the Dale Head site when compared to the other limestone pavements studied. This species is also common to Britain and Ireland, found in leaf litter, woods, hedges and especially abundant in calcareous soils (Cameron, 2003). This species is especially sensitive to light and desiccation and is quoted to be "unhappy in any but a saturated atmosphere, and it totally avoids light" (Morton, 1954). Although Dale Head does not contain the deepest grikes which may provide the darkest and most humid conditions, this site is one of the most humid for a given depth alongside High Folds which contains the second greatest occurrence of *Carychium tridentatum*. In Dale Head and High Folds, this species is found in shallow grikes, whereas in all other sites it was recorded from samples from grikes which were extremely deep.

Lucilla singleyana was not found in High Folds but was found in both of the other British Limestone pavements. This species is not found in the Republic of Ireland and found sparsely throughout Great Britain and is more commonly found in subterranean environments. Willis (2011) recorded that a pavement close to this site has a mean soil depth of 283.3mm, which is the third largest in that study. While this does not confirm that High Folds has a substrate which can accommodate *Lucilla singleyana,* it is a positive indication. The reason for this species absence is not known owing to the lack of information on its habitat and ecology (Alexandrowicz, 2010).

Discus rotundatus was not found in the grikes of the Turlough More site but was found in all other sites. This species is very common in both Britain and the Republic of Ireland and is usually found in woodlands and hedges (Cameron, 2003). Although this is considered a woodland species, this study and others have shown that the microclimate of a grike is comparable to that of woodland and fosters many similar species (Dickinson et al., 1963). Despite this microclimatic similarity *Discus rotundatus* is recorded to prefer sites with coarse woody debris, which may explain the high presence on sites such as Holme Park Quarry (Kappes, 2005). The preference for coarse woody debris does not fully explain the absence on Turlough More, as sites such as Fanore with equally as little woody debris contain this species. The absence of *Discus rotundatus* may, however, be explained by the observed preference of this species for shallower grikes. While shallow grikes were present in Turlough More, comparatively fewer were sampled at this site than any other.

Biogeography appears to have played a large role in the differentiation of invertebrates found between sites. While this is a finding of interest, the variation of features such as location, altitude, slope, aspect and intensity of grazing may, however, have masked other findings relating to grike microclimate. This topic will be discussed further in the limitations of this study.

7.4.2.2 Species richness and invertebrate count

7.4.2.2.1 High invertebrate count within a limited number of species

The Turlough More site was found to have the greatest number of invertebrates found within its grikes; however, the range of species that predominated on this site was extremely limited. This limited range of species is observable from the isolation of Turlough more in Figure 7.10, brought about by a large number of only two species. Although the greatest number of invertebrates was found on this site (1711) they belonged to only 14 species, and most sampled invertebrates were from the species *Punctum pygmaeum*. This combination of factors resulted in the Turlough More site receiving the lowest Shannon diversity index. *P.pygmaeum* appears to favour deeper grikes over shallower ones. The preference for deeper grikes is evidenced by the reduced frequency of this species in the High Folds site and a large number in Turlough More. It is possible that *P.pygmaeum* is the species best adapted to the deep grike habitat of those studied. This is demonstrated by the significant Spearman Rho correlation coefficient when comparing prevalence and depth ($p < 0.05$). An explanation of the predominance of *P.pygmaeum* may be that it is partway toward competitive exclusion of other species from the deeper more stable grike habitats. The competitive exclusion principle or Gause's law dictates that two species which have the same ecological needs cannot occupy the same spatial niche (Hardin, 1960). One species adaptation, will over time, give it a competitive advantage and competitively exclude the other species from this niche. In reality, this occurrence is mainly limited to laboratories where it was first conceived by Georgy Gause, who observed yeasts *P. aurelia* and *P. caudatum* competing for food (Gause, 1932). This exclusivity to laboratories is because in a laboratory the number of variables influencing survival is severely limited, whereas, under a given set of conditions, a true ecological niche balance is never achieved, giving no one species the upper hand for survival (Hutchinson, 1961). It has, however, been shown experimentally, that by removing survival variables, species diversity is reduced (Paine, 1966). A limestone pavement grike presents an environment where the variables influencing survival are reduced with depth, and this has possibly allowed *P.pygmaeum* increasing dominance with depth. This scenario is, however, brought into question by the apparent lack of competitive exclusion observed in soil biota (Bardgett, Yeates & Anderson, 2005; Wardle, 2006)

7.4.2.2.2 Low invertebrate count over a wide range of species

The grikes of Dale Head and High Folds experience the reverse of Turlough More. The PCA grouped these limestone pavements because they contained a low number of the more common invertebrates, but a high number of species. Dale Head and High Folds support 39 and 43 species respectively, whereas they only produced 443 and 241 invertebrates in samples. It is difficult to explain the increase in species diversity in these two sites without further exploration, due to the wide number of theories describing the conditions for high diversity. One possibility is the "Intermediate Disturbance Hypothesis". Under these conditions, the environment is neither too harsh to limit the species ability to survive nor too stable as to encourage the competitive exclusion discussed previously (Ward & Stanford, 1983). This niche is exemplified in England et al.'s (2008) study of coral reefs where species diversity is greatest where wave activity is neither too severe nor too gentle. It has been shown in Chapter Four that the upper zone of a grike experiences higher variation in light intensity and more rapid shifts in temperature, but also that the base of a grike provides an increase in relative humidity. It may be that in a shallow grike the selective pressures of the external environment are neither too harsh nor too stabilised, thus allowing a wider diversity of species to survive though in a smaller number. The humpback pattern in population number indicative of an intermediate disturbance is not, however visible in the data from this study. The lack of a humpback distribution is perhaps because no grike has exhibited an environment of sufficient disturbance to limit population size or because the distinctive humpback population gradient does not apply to soil-dwelling biota (Decaëns, 2010).

7.4.2.2.3 High variance

Turlough More and Fanore had the highest variance in the number of invertebrates collected in each pot. Turlough More pots contained between 4 and 197 invertebrates with a variance of 23.61. Fanore pots contained between 0 and 92 invertebrates with a variance of 1.73. The reason for this may in part be due to the two ecological principles discussed combined with the fact that these sites had the widest range of grike depths. The number of invertebrates collected correlates with depth, as discussed in the next subsection. It is then logical for the pavements with the widest range of depths to have the widest range of invertebrates found in each sample.

7.4.3 Invertebrates and Depth

7.4.3.1 Invertebrate abundance and depth

The results of this survey of limestone pavements have shown that there is a significant correlation between grike depth and the number of invertebrates sampled, as demonstrated using Spearman's Rho and shown in figures 7.16, 7.18 and 7.20. As previously discussed it is possible that the greater number of invertebrates found with increasing depth may be due to the proliferation of a small number of well-adapted species to the deeper grike as was observed in Turlough More. It is also possible that a deeper grike provides a greater space for invertebrates to inhabit with greater resources or deeper grikes have inherent qualities such as microclimatic stability, making them a more attractive environment. The possibility of having sampled from the whole grike is discussed as a method limitation later in this chapter. A deeper grike may provide more space and resources for a larger number of invertebrates to thrive, however considering the determinants of population size such as predation, competition and disease it is unclear how a deeper grike presents an advantage. Food availability may not also be greater in a deeper grike as the species sampled are mostly saprophytes and detritivores. This means that they will produce enzymes to decompose plant matter found at the bottom of the grike or eat only decomposing material found on the grike floor (Chown & Nicolson, 2004). Therefore, these species consume food found in the highest concentrations at the bottom of the grike (Harding & Sutton, 1985; Cameron, 2003). Alternatively, microclimatic stability may act to protect the species within the grike from population decline caused by adverse weather conditions outside the grike allowing the population to grow to the potential carrying capacity unimpeded (Pachauri et al., 2014). In either case, it appears that deeper grikes have a greater carrying capacity than shallower grikes. Carrying capacity in this context refers to the number of individuals which can use a resource without causing it to degrade (Warf, 2010).

There are not defined invertebrate species ranges as were found with floral species (Silvertown, 1982), indicating that no species bioclimatic envelope confines them to any specific area of the grike. As previously discussed, it is possible that the carrying capacity of the habitat is linked to grike depth as a result of greater space or the availability of more stable microclimates. If this is the case, based on the assumptions of ideal free distribution, there should be a greater number of invertebrates sampled from a deep grike. Ideal free distribution is a model to describe the distribution of fauna between habitats of differing values (Pettifore, Norris & Rowcliffe, 2000). Ideal free distribution is founded on the principles of game theory and states that individuals are free to distribute themselves between resources of differing value until equilibrium is reached. Ideal free distribution has been observed in insects such as aphids. Authors observed that as plants which were most preferred

became more densely populated with aphids, and the average individual fitness of aphids decreased. At a certain point, other less preferred plants became populated until equilibrium was reached. This equilibrium represented the carrying capacity of each plant (Whitham, 1980).
Ideal free distribution relies upon the following:

- Free movement of individuals without a cost to their survival
- The ability to make maximum use of the resources available
- Each competitor must be equal in foraging ability or other required skill

The ideal free distribution also considers the following; however, this does not always apply:

- Ideally, competitors should have perfect knowledge of the resources available and the behaviour of their competitors (Pettifore, Norris & Rowcliffe, 2000).

It is unclear if limestone pavement grikes in Britain and Ireland allow free movement of snails from one grike to another. However, this behaviour has been observed in other countries (Fröberg, Stoll, Baur & Baur, 2011). Each animal's ability to maximise gains and compete on an equal level is not known and may be subject to further study.
On balance it cannot be stated categorically that the number of invertebrates sampled in a grike is described by ideal free distribution. However, it appears possible. As has been previously stated the correlation between depth and invertebrate number describes an ideal free distribution on the assumption of depth being a preferred habitat feature. It has also been hypothesised that competition is not a large influence on population size in soil-dwelling biota, whereas the availability of resources is a large driver of the increased population (Bardgett, Yeates & Anderson, 2005; Wardle, 2006). This is the case in woodlice, where the number sampled increases monotonically along an increasing gradient of resource availability (Paoletti, 1988). If this is true for grike biota, it will reduce the likelihood of competitive interactions which are relied upon for other models of distribution such as ideal despotic distribution (Sutherland, 1996)

7.4.3.2 Species diversity and depth

It has been stated in previous studies of limestone pavement mollusc distribution that diversity increases with average grike depth (Nicholls, 2009; Norris & Willis, 2010). Cave studies oppose this view, stating that diversity at the surface is considerably wider than inside a cave (Culver & Sket, 2000). Previous studies of grikes differ from the current study in two ways. Firstly, they used a visual searching methodology and sieving leaf litter where appropriate. Consequently, the depths reached by their studies are limited by the observation depth and reach of the surveying teams. Secondly, the previous studies of grikes used average grike depth for the analysis of species richness, not specific grike depth. Methodologies such as this give a generalised pavement level significance of depth on species richness, not an analysis of richness per grike.

The results of this study have allowed further specificity of the relationship between species richness and depth by directly correlating the species richness and depth within one grike. The methodology used in this study has shown that close to the surface of the grike the diversity of species is moderate and decreases with depth until, at around 100cm, it increases and remains high before reducing once more. When compared to the microclimate stability at different depths in Chapters Four and Five, there appears to be some possible connection between invertebrates and the microclimate in which they are found. Subsection 4.3.2 discusses the observation that for the grikes in this study there is a point at 75cm, where microclimate becomes more stable, attributable to a reduction in light intensity in the grike, as described in Subsection 4.3.3. In this survey of invertebrate diversity, there appears to be a similar transition point centring on 75cm where before and after diversity is relatively high, but at around 75 cm, diversity is lower.

It must be acknowledged that the locations surveyed as part of the invertebrate sampling are from the bottom of the grike, whereas microclimate records are taken from all areas of the grike. This is discussed in greater detail in the limitations of this chapter.

7.4.3.3 Zonation in the grike

By analysing multiple variables concerning grike depth, it was found that zones similar to those observed in other areas of the study have also been observed in the number and type of invertebrate surveyed.

Upper zone

- Contains few *P. pygmaeum* or *P. pusilla*, but a larger number of *Discus rotundatus.*
- Has a low number of invertebrates compared to other zones
- Contains little variation in the number of invertebrates found in this zone.
- Has higher species diversity than the transition zone but a lower one than the lower grike.

Transition zone

- Contains few *P. pygmaeum* or *P. pusilla*, but a larger number of *Lauria cylindracea.*
- Has higher numbers of invertebrates than the upper zone but fewer than the lower zone.
- There is some variation in the number of invertebrates found in this zone at certain depths.
- Has low species diversity.

Lower Zone

- Dominated by *Punctum pygmaeum* and to a lesser extent *Pyramidula pusilla*
- Has the highest number of invertebrates when compared to other zones.
- There is the greatest variation in the number of invertebrates compared to other zones.
- Has high species diversity.

7.4.4 Invertebrates and orientation

This study found there to be no significant difference in the abundance of invertebrates or number of species in EW and NS grikes. By not finding any significant difference between grikes of differing orientation, these findings are contrary to those of prior orientation focused surveys that found greater diversity in NS grikes (Inman, 2000; Lloyd-Jones, 2001). This discrepancy may be in part be due to differences in the methodology used. This study was able to survey deeper grikes than was previously possible, and vacuum sampling has been shown to favour smaller species (Doxon, Davis & Fuhlendorf, 2011). These differing findings highlight the advisability of multiple different methods of surveying for invertebrates in grikes.

7.4.5 Limitations

7.4.5.1 Invertebrate extraction

The methodology for the extraction of invertebrates from the grike was designed to target those invertebrates at the bottom of each grike specifically. In theory, this should make the sample area for each grike the same and reduce the chance that deeper grikes record more species by being larger habitats. There are possible flaws in this methodology, allowing for incidental samples from the whole grike. Firstly, there is a potential for invertebrates from the walls of the grike to be dislodged by the action of moving the hose nozzle, resulting in higher numbers of invertebrates being sampled from deeper grikes. It is also possible that invertebrates such as snails congregate toward the base of the grike during the day where conditions are most hospitable, only making use of the whole grike and surrounding area during the night when external conditions are habitable (Fröberg, Stoll, Baur & Baur, 2011). This means that during the day, there are abnormally high concentrations of invertebrates at the base of the grike.

The extraction method was also designed to create enough suction to collect all possible grike invertebrates; however, no Carabidae were collected in this study while other studies of the grike fauna using other methodologies identified a number of Carabidae species (York, 2009). This raises the possibility that the method used was flawed.

By sampling only the base of the grike, this method of invertebrate capture ignores species which may only be present on the walls of the grike and not found at the grike base. This also means that invertebrates with a requirement for less stable conditions than is available at the base of the grike may not be assumed to be found in deep grikes.

In a future study, pitfall trapping may be used to avoid disturbing the walls of the grike, sample only those invertebrates found at the base of the grike and overcome the issue of providing the suction needed to collect larger invertebrates. This method would, however, not overcome the possibility that higher concentrations of invertebrates are found in the base of the grike during the daytime. The pitfall trapping method was also used previously to sample invertebrates from grikes, where it was found that installing pitfall traps at large depths was not possible (York, 2009). The respective merits and disadvantages of different sampling methods highlights the need for multiple techniques to be used when investigating grike invertebrates.

7.4.5.2 Direct comparison between sample location and microclimate

This study attempted to draw the closest comparisons possible between the location of invertebrate samples and the microclimate of the grikes used for sampling by using the same sites in both microclimate and invertebrate studies. There are, however, differences in the microclimate between the bottoms of grikes from which invertebrates were sampled and the body of the grike from which most of the microclimate measurements were taken.

In Chapter Four, it has been shown that the microclimate of the bottom of a grike does not have a different temperature or level of light intensity to any other section of grike of a similar depth. The bottom of the grike does, however, have a higher level of relative humidity when similarly compared. The difference between the microclimate of the grike bottom and that being sampled means that the environment in which invertebrates have been samples may be assumed to be higher than that which has been identified through measurement.

The maximum depth from which grike base relative humidity was measured in this study was 125cm. As such, there is a limit to how much can be interpreted about the relative humidity of the particularly shallow grikes especially in light of the results from Chapter Five showing that upper portions of the grike are particularly prone to air currents which interact with the external environment. This discrepancy only affects the upper zone, and to some extent, the transition zone, as the finding from Chapter Four also shows that at a depth of 100cm and beyond the grike is almost constantly close to 100% relative humidity.

In future studies such as this, it may be more accurate to conduct a short-term microclimate study that combines species collection and collection of microclimate data from the base of grikes. This was not possible in the current study due to the large number of microclimate loggers required, but such actions could be considered in more highly resourced projects.

7.4.5.3 Influence of biogeography on invertebrates

It was identified as part of this study that biogeography has played a large role in influencing the presence, absence and number of invertebrates of different species found within the grikes of this study. The purpose of this chapter, however, was to “provide analysis concerning microclimate” and not biogeography. By basing the selection of sites on those used in the microclimate study, several extra influences have been introduced to this study which may have masked the influence of microclimate on the invertebrates of the grike. This is exemplified by the need to remove High Folds from some analyses because it did not share common properties with the other sites.

If all the grikes sampled had been from the same pavement and biogeographical factors had been kept to a minimum, it may have been possible to identify depth ranges for a wider number of species. Future studies of the link between grike microclimate and invertebrates should limit the external factors influencing species by restricting sampling to a smaller geographical range, in order to make conclusions less ambiguous.

7.4.5.4 Small sample size

The sample size of 30 used in this study is toward the smaller acceptable size for a stratified sample and samples were taken from a small number of sites when compared to the breadth of limestone pavements available for study in Great Britain and the Republic of Ireland (Schweiger, Steinbauer, Dengler & Beierkuhnlein, 2016). Were sample size to have been more representative of the area under study a larger data set would have made it possible to more accurately appreciate the influences of site-level features such as elevation, coastal proximity and surrounding habitat. For example, further sites in close proximity to broadleaf tree species would provide further evidence to either confirm or refute the link between these species of tree and *Lauria cylindrace* in a limestone pavement. A greater breadth of sites would also have allowed for a more detailed investigation of some pavement level features. In the current study, only one site contained grikes positioned 45° to the cardinal compass directions, a greater number of such sites would have allowed for the direction of the grike to have been explored in greater depth. Were this study to have included more sites and a greater number of samples per site it may have been possible to collect a greater diversity of invertebrates from the grikes. It is recommended that a follow-up study collect a greater number of samples from more locations, or to focus a study on one pavement type or location in order to more clearly represent the influence of limestone pavements and their surroundings on the invertebrate life found within grikes.

7.4.6 Future study

This chapter highlighted several gaps in knowledge which future study may pursue.

7.4.6.1 continuation and expansion of invertebrate surveying

To the knowledge of the author, this chapter has provided the first insights into the invertebrate life found at the base of some of the deepest grikes. A modified survey approach which acknowledges the limitations of this study could usefully be employed as a form of monitoring, in order to record and better understand the impacts which climate change has on aspects of grike fauna. Were this study to be continued it may be beneficial to expand any surveying to any limestone pavements proposed for further microclimatic study in Subsections 4.4.10.2 and 6.4.3.2.

Discussion in this chapter put forward hypotheses to explain the reasons for high diversity in small populations of invertebrates found in shallow grikes. Further fieldwork which included grassland and shallower grikes may be able to identify whether these environments receive sufficient disturbance to produce the humpback pattern in population number suggestive of an intermediate disturbance. Future studies should also acknowledge the limitations of this study and seek to overcome them by directly identifying the microclimate of grikes being sampled and use a range of sampling techniques to understand the range of invertebrates present.

7.5 Conclusion

Through surveying the invertebrates of a series of limestone pavement grikes with varying characteristics, it is possible to make some conclusions relating to the invertebrates and microclimate of grikes.

The zonation observed in the microclimate has been borne out to some extent within the invertebrate counts. The grikes shallower than 60cm have some of the highest species diversities in the study, and also some of the lowest invertebrates per sample. This was proposed to be explained with the disturbance hypothesis, which relies on the disturbance provided by the evidence of rapid microclimate change provided in Chapters Four and Five. The upper zone of the grike has been found to have more rapid temperature change, greater variance in light radiation and greater variance in relative humidity. This zone may have provided the conditions of disturbance required for the observed species diversity.

The region below 100cm has been described differently in different grikes; either there was a large number of diverse species or a large number of only one species. It was hypothesised that the large number of invertebrates and species might be predicated on stability, creating increased carrying capacity within the environment. Whereas, hypothetically a large number of one species could be linked to the exclusion principle, which also requires a large degree of stability. Either way, the zone below 100cm requires stability, which was present in most grikes in this study below 100cm. Chapter Four has shown this deeper zone contained considerably reduced insolation, slower changes in temperature and almost consistently high relative humidity when compared to the rest of the grike.

The zone between 60cm and 100 cm was found to have low species diversity but still more invertebrates counted than in the shallower grikes. In terms of microclimate, this area is may be a transitional zone between the upper and lower grike, and it appears that it is also a transitional zone for invertebrate diversity and number per sample.

The strongest connection between geodiversity, microclimate and invertebrate biodiversity found in this chapter, was the increasing number of invertebrates sampled as depth increases. This highlights the possibility that a more stable microclimate has a greater carrying capacity and that these two features of a grike are intrinsically linked. If it is the case that severe weather events are to increase in frequency (Pachauri et al., 2014), this places species in the upper zone of the grike in the greatest danger, whereas those in the lower grike are less affected. Chapter Six has indicated that as global mean temperature increases, the temperature within the grike also increases but to a lesser degree. By observing the distribution of invertebrates within the grikes in the survey and within other habitats, it is unlikely that the crucial tipping point of the thermal performance curve will be reached for many invertebrates within the parameters simulated in Chapter Six. However, species ranges may be forced down vertically into the grike in a similar way to the ranges of mountain species being forced upward (Root, Price, Hall, Schneider, Rosenzweig & Pounds, 2003). Species may also be affected by indirect effects of climate change which may influence their health (Masters et al., 1998). The further study proposed as part of this chapter will advance the findings made here.

8. Discussion

Each of the chapters investigating the grikes of the limestone pavement has built a continuous body of research which advances the understanding of this habitat. It is the intention of this work that it will be advanced upon to guide effective management of limestone pavements in the context of climate change. The evidence base for this study has been built using the methodological structure outlined in Chapter Three. Chapters Four and Five identified the characteristics of the grike that may influence how climate change may act on the microclimate. Chapter Six refined the assumptions made in prior chapters using simulations to create a plausible future scenario for the grike. Chapter Seven discussed the fauna living within the bottom of grikes and explored the relationship between invertebrates and the grike microclimate.

This discussion reaffirms what has been learned about the grike microclimate and inhabitants, and provides a road map for further stages of research.

8.1 How does the grike form underpin the varied invertebrate biodiversity of the grike bottom?

Tutor and mentor to the author, Cynthia Burek has often stated that “Geodiversity underpins Biodiversity” (Burek, 2001). Limestone pavements provide a geological feature which plays an important part in enhancing the biodiversity of a landscape by providing a sheltering microclimate (Gray, 2013). This thesis shows that within a limestone pavement, the grikes also may provide an element of geodiversity. This geodiversity may be added through the variation in shape and orientation brought about by the processes which interacted in their formation. In turn, the variety of grikes available provides a range of microclimates for habitation and enhances the invertebrate biodiversity of the grike bottom and with that the pavement. Using the definition of geodiversity provided by Stanley (2001), this would mean that a single limestone pavement contains a varied geodiversity.

8.1.1 Generalised description of the grike microclimate

It was shown by this thesis that the deeper limestone pavement grikes that were sampled provided a more substantive level of stabilisation to the microclimate that was found within them. This stabilisation is hypothesised to be due to internal and external forces. The internal influence on the grike is hypothesised to be due to the volume of limestone surrounding each grike. The limestone is suggested to provide a body with high thermal mass which absorbs and releases heat to the air within the grike. The amount of heat energy transferred from the limestone to the air in the grike is suggested to increase with depth, as the surface area between these two bodies is increased. The grike is also suggested to be influenced by the heat from solar radiation and heat carried by air entering the grike from the external environment. Deeper areas of the grike are hypothesised to be influenced less by these forces due to the limited range of direct light entering the grike and the disturbance of air currents interacting with the grike entrance. Simulations show that the influence of external forces can also be modified by other formation characteristics of the grike such as lip shape, width and orientation.

Evidence from the grikes which have been studied has indicated that the balance between microclimate disturbance and stability does not change linearly along a depth gradient. Instead, there may be two zones within the grike and a transitional zone between them. The zonation of the grike has been demonstrated throughout this study; in Chapter Four, it was indicated that temperature changed rapidly in the upper zone and slowly in the lower zone. Later in the same chapter, light simulated and measured in the upper zone appeared more variable in the upper than in the lower zone. In Chapter five, airflow in the simulations was more variable in the upper zone compared to the lower zone, and this may have impacted the variability of relative humidity in each zone. A similar layering was found by Yarrington and Beasleigh (1969) who described a layer of stable temperature and relative humidity in the lower two-thirds of a grike.

From the evidence in this study, it is proposed that the upper zone of the grike is located between the surface and 75cm of depth. In the upper zone, it is suggested that the surface climate is the primary influence over the microclimate and the insulation and physical protection of the limestone is less substantial. Below a depth of 100cm into the grike, the sun and air movement were observed to have less influence on the microclimate and the relatively more thermally stable limestone may stabilise the microclimate. Between the proposed upper and lower zones, there is a possible transitional area.

8.1.2 The Upper grike zone - above 75cm

<u>8.1.2.1 Cause</u>

Simulation of the insolation in the upper grike has indicated that this zone experiences a higher intensity and duration of solar heating due to diminished shelter from the grike walls. The observations from Chapter Four indicated that the orientation of each grike influenced the way light impacts all depths. When compared to other zones, the variation in grike orientation had a more substantial effect in the upper zone due to the higher intensity of light impacting toward the grike surface. The simulation indicated a gradual change in light incident on the EW grike, over the day, whereas the NS grike was simulated to have rapid changes to light intensity, resulting in meaningfully high levels of light recorded only at midday. The findings of the simulation were replicated by the measurements taken from the grike in Chapter Four. Chapter five indicated that there is a vortex of moving air on the surface of a grike. The depth to which this vortex reaches is highly dependent on the width and lip shape of the simulated grike. This vortex is likely to bring air from outside the grike with a different temperature and relative humidity, which combines with air in the upper grike. Based on the shape of grikes from over 40 limestone pavements it can be proposed that a large number have the potential to contain a vortex of mixing air restricted to the upper zone (Willis, 2011).

8.1.2.2 Effect on microclimate and invertebrates

In Chapter Four, it was observed that the fluctuations in temperature in the upper zone of a grike were highly dependent on season and time of day. This dependence on external macroclimate produced a broad spread in the range of temperatures recorded in the upper zone of the grike. The rate of temperature change was rapid and was considerably more rapid in a positive direction. The temperature change in the upper zone occurred with little delay when compared to changes in the surface temperature. Grikes of differing orientation had a more substantive difference in temperature within the lower zone when compared to the upper zone. Temperatures in the upper zone were typically higher in EW orientated grikes, and NS orientated grikes experienced shorter periods of high temperature over midday. The light intensity in the upper grike zone was highly seasonal, experiencing comparatively high levels of light for the duration of the day. The relationship between light intensity and orientation in the upper grike mimicked the temperature. The EW grikes studied experienced higher light intensity at the start and end of the day, whereas the NS grikes experienced higher light intensity at midday.

The relative humidity of the upper grike was described in Chapter Four as being more seasonal, more changeable and reached lower values than in other zones of the grike. The hour of the day strongly influenced the relative humidity in the upper zone of the grikes that were studied. There was a discernibly lower relative humidity recorded in the NS grikes when compared to the EW grikes. Chapter Four also hypothesised that moisture in the grike floor substrates increased the humidity of the air within the bottom of the grike. This means that in shallower grikes, the relative humidity may be less influenced by the processes discussed above. The hypothetical role of grike bottom substrates is based on the relative humidity of grikes with a maximum depth of 125cm and as such, there is a limit to how much may be applied to grikes shallower than 75cm. The more considerable influence of external conditions on the upper zone of the grike means that severe weather may influence this region most strongly. During the colder winter studied, the temperature of the upper grike zone dropped below that of other regions of the grike and dipped below 0°C. During the hotter summer selected for study, the upper zone stayed warm and experienced a higher number of very hot days. After heavy rainfall, the upper grike of the two sites studied dried out more quickly than the lower grike.

Of those sampled, the invertebrate life found in the shallower grikes lying within the upper zone was relatively diverse but low in abundance when compared to grikes containing other regions. This is possibly due to the disturbance hypothesis as detailed in Chapter Seven.

8.1.3 Lower grike zone - below 100cm

8.1.3.1 Cause

It was hypothesised in Chapters Four and Five, that two main factors are influencing the temperature stability of the lower grike. Firstly, the restricted opening of the grike to the surface may limit the amount of air mixing with the external environment and reduce the heat radiated from the sun that reaches below 100 cm in the grike. Secondly, it was suggested that due to the thermal properties of limestone, the rock surrounding the grike might absorb heat energy during the summer and gradually lose heat to the grike environment over winter. The effect of which, may mean that the body of relatively low-temperature rock, cools the air in the lower grike zone during the summer, and in winter the rock is a relatively high-temperature, heating the air in the lower grike. These hypotheses may be born out by a future study of the grike.

8.1.3.2 Effect on microclimate and invertebrates

The temperature of the lower zone of the grikes that were studied experienced comparatively little daily or seasonal fluctuation when compared to the surface and other zones. The temperature deviated from the mean very little at this depth, and as a result, the maximum and minimum temperatures reached were considerably closer to the mean when compared to the upper grike. The rate of temperature change was slow in the lower grike zone, and the positive and negative changes in temperature occurred at a similar rate. When temperature changed at the surface of the grike, there was a measurable lag period before temperature changed at depths in the lower grike zone. This lag increased as the depth and magnitude of temperature change increased. The effect of orientation in the lower zone of the grike was less dynamic than in the upper zone. During summer the EW grike was found to be warmer than the NS grike for most of the day, but the grike temperatures became more comparable toward midday. This differentiation between the different grike orientations was reduced in winter and as depth increased.

The reduction in the amount of direct light impacting the grike beyond one metre is hypothesised to have resulted in considerably less light intensity recorded in the lower grike zone. At 125cm there were infrequent moments where light reached this depth, and from 175cm the light intensity was frequently indistinguishable from zero. The difference in light intensity was also affected less by the orientation of the grikes at lower depths. For the majority of the time, the EW grikes recorded fractionally higher light intensity than the NS grikes; however, at a depth of 125cm in winter the NS grikes recorded more light than in the EW grikes. The difference in light intensity between the two orientations was hypothesised to be due to the angle of the sun allowing direct light to potentially extend beyond 100cm in the NS grike, but not the EW grike when simulated.

The relative humidity in the lower zone of the grikes studied was consistently higher than in the upper zones, and there was also less seasonal and diurnal change in relative humidity. The effect of orientation on relative humidity was also weaker in the lower grike zone. Relative humidity in the lower zone of NS grikes was recorded to be slightly diurnal and higher than in the EW grikes on average.

Severe weather affected the lower region of the grikes considerably less than at the surface or the upper zone of the grikes. Short periods of severe cold or heat impacted the lower grike zone to a lesser degree and after a longer time lag than in the upper zone. During more extended periods of high temperature, the difference between the upper and lower zones decreased; however, the rate of change in the lower zone became slower, the further the temperature deviated from the mean. The relative humidity in the lower grikes remained very high during periods of severe rain.

The invertebrates of the grikes with a depth extending to the lower zone are comparatively plentiful when compared to shallower ones. The diversity of life in the grikes which were studied appears to have been dependent on the presence of species *Punctum pygmaeum*. If *P. pygmaeum* was present, this species tends to dominate the grike, whereas in the absence of *P. pygmaeum* there was a high diversity of invertebrate life in the lower grike zone.

8.2 Future for the grike

8.2.1 Microclimate

Chapter Six contains climate simulations from the UKCP18/ RCP8.5 emissions scenario, which it is considered to be a very high baseline emission scenario, and as such results in this thesis projects temperatures which while plausible are toward the high end of those likely to occur (Pachauri et al., 2014). Projections are taken from 15 models, and nine locations for 2010 to 2099 have formed the basis of a plausible future scenario for the grike temperature. The nine locations selected represent the largest concentrations of limestone pavements in Britain and Ireland. As discussed in Subsection 6.4.3.1.3, these locations do not cover all limestone pavements, and the confidence in the conclusions made in this study should be considered lower for sites outside the sampled area.

The results of the microclimate simulations made in Chapter six have indicated that the features of the grike that have created the grike microclimate are likely to continue to provide stability. There may be some zonation as observed previously; however, this is not a feature of the simulation and cannot be confirmed in the future. There was simulated to be a disparity between the temperature at the surface and in the grike, which increased over time and grike depth. Chapter Four has indicated that the grike microclimate is largely sheltered from the severe weather experienced in this study. It has been suggested that the grike is likely to continue to provide shelter if severe weather events of this magnitude continue, however, if the severity and frequency of events increase in the future the protection of the grike is uncertain (Pachauri et al., 2014).

Stability of the grike microclimate may, however, have limits. The mean grike temperature was indicated to increase by 0.58°C (100cm) and 0.45°C (200cm) per decade under the RCP8.5 emissions scenario. Any effect this may have on relative humidity is likely to focus on the upper zone of the grike and may make this region more hostile in combination with higher temperatures. The impact of climate change on the light intensity experienced by the grike is likely to be different depending on pavement latitude. In the more southern pavements such as those in South Wales, cloud cover is expected to decrease. Decreased cloud cover exposes grikes to higher light levels, whereas in Scotland cloud cover may increase, thereby reducing light exposure (Jenkins et al., 2009). Based on current patterns of light exposure in the grike, it is expected that impacts and change to light levels are most likely to impact the upper grike zone.

8.2.2 Invertebrates

Based on the results of this study, there are two possible future extremes for the species inhabiting the grike.

8.2.2.1 Non-microrefugia

Under this condition, the grike does not provide a microclimate which supports life in its current state, and disturbance brought about by climate change compromises the grike inhabitants’ fitness. This scenario is due in part to the change in climate and the adaptability of the species inhabiting the grike. As discussed in Chapters Two and Seven, the direct implications of climate change on a stabilised microclimate are changing the ranges of species within their habitat; however, the certainty with which predictions may be made is limited by the tools and resources available. There are also other indirect impacts of climate change which need to be considered for refugia, which may also impact the future suitability of a habitat for each species (Rull, 2009; Suggitt, 2012).

Changes in the habitable range can have implications for a species ability to breed (McCarty, J.P., 2001), changes to phenology can affect the ability to find food (Root, Price, Hall & Schneider, 2003) and changes to the lifecycle or location of species within the food web can have unknown further consequences (Walther et al., 2002). Additionally, if a species cannot keep up with their changing range, they face the threat of competition from species with greater thermal tolerance (Baur & Baur, 1993; Davis & Shaw, 2001; Parmesan, 2005) which if allowed to thrive could result in local extinction of more sensitive species. In their place, the thermophilic species are more likely to thrive due to their comparative tolerance for higher temperatures (Thomas et al., 2011). A similar phenomenon is already taking place in some caves and beginning to threaten the inhabitants through predation and competition (Wynne et al., 2014). Such invasions into the grike habitat are theoretically possible as changing conditions make species current ranges less habitable (Oliver, Brereton & Roy, 2013).

The probability of a non-microrefugia condition occurring inside a grike is highest within the upper zone where most of the interaction between macroclimate and microclimate occur. This places shallower and wider griked pavements in Group 7 of Willis's Groups discussed in Subsection 3.3.1 (Willis, 2011), at the greatest risk of high climate change impact. Group 3 pavements may face additional stresses due to harsher maritime conditions or saline incursions as sea levels rise (Pachauri et al., 2014).

8.2.2.2 Refugia

Chapter Two of this thesis describes microrefugia as notoriously difficult to define however elements of thermal stability, and variable microhabitats predominate in the literature (Rull, 2009; Suggitt et al., 2012; Hannah et al., 2014). This study has been able to illustrate that the lower zone of the grikes within this study contains a microclimate that is more stable than that of any other zone or the external macroclimate. Simulation has provided a plausible future scenario for the grike habitat is an area where the temperature may change, but deeper zones temperature may remain stable within the context of their macroclimate. The invertebrates found within the grikes are predominantly generalists found in less stable habitats such as scree slopes, hedges, rough grassland, gardens and dunes. The number of invertebrates sampled from grikes positively correlates significantly with depth, and it is hypothesised that this may be linked to microclimate stability. There are species identified by this study which are found predominantly in woodlands and wetlands. For a number of these species, it may be that the future microclimate of the grike remains sufficiently stable for a grike to be considered a possible microrefugia however further study is required to state this definitively.

If it is accepted that there is a connection between microclimatic stability in the grike and potential for microrefugia. The lower zone of the grike is most likely to provide mobile species with a region which they can inhabit to provide shelter from climate change. The deeper grikes found on Willis's Group 6 pavements (Willis, 2011) are the most likely Group, to provide such a microrefugia. Group 1 pavements such as High Folds may have potential for species requiring microrefugia in Great Britain, as high elevation species are at greatest risk of range loss (Sala et al., 2000). In the Republic of Ireland and Great Britain species found in the coastal (Group 3) pavements could also face similar limits to dispersal if more northerly latitudes are blocked by areas of sea as may be the case for Fanore and the Great Orme. The upper zone in a grike from any pavement grouping may have the potential to provide a refugial microclimate to hardier species. These species which can tolerate the indicated changes to the microclimate are most likely to be those that have behavioural or physiological adaptations to thermal stress (McQueen & Carnio, 1974).

8.2.2.3 Implications for conservation

The conservation philosophy outlined at the start of this thesis holds that species and habitats are to be conserved for their intrinsic value and not the value they hold for the human population. Both diversity of organisms and ecological complexity are good, and that conservation must occur within the context of human-altered landscapes and climate change (Soulé, 1985) (Kareiva & Marvier, 2012). The conservation philosophy of this thesis is explained in greater detail in the methodology in Chapter Three.

The prospects for any non-microrefugium grike in a warmer climate are detrimental to the conservation status of the habitat under the defined goals of this thesis. The shallow grikes which may be considered least likely to be microrefugia and most impacted by climate change were found to contain a moderate amount of species diversity when compared to other depths of grike. Areas of the grike close to the surface of the pavement were found to have a large proportion of the flora identified by Silvertown (1982). Many of the species which are found in the grike habitat have a preference for stable temperatures, lower light and higher relative humidity. This preference is exemplified by the species of mollusc identified as part of this study (Appendix 4) and Ward and Evans' study of grike flora (1975). In a harsher climate, the existing threats are exacerbated, and the already occurring reduction in species richness observed on limestone pavements is likely to increase (Margules, Nicholls & Usher, 1994; Thom et al., 2003; Travis, 2003).

Despite the possibility of a microrefugium, the conservation status of even deeper grikes may be at some level of risk. All species are part of interactive networks which will be damaged to a lesser or greater degree by climate change (Devictor et al., 2010). Within this network, it is often the more complex ecological interactions which suffer most (Schweiger et al., 2010). Although most species identified in this study have been generalists, there is evidence of complex interactions between flora and fauna that may suffer (Webb, 1961).

If conservation is considered on a national scale, there are some species which may be at higher risk of national extinction should limestone pavements not be managed for climate change. These include the Rigid Buckler-Fern which is restricted mainly to grikes and the Moss Chrysalis snail (*Pupilla muscorum)* which is in decline in Great Britain. The rarity of species is not prioritized as part of the conservation philosophy of this thesis; however, loss of biodiversity within the habitat is considered detrimental.

8.3 Further research required in order to manage the limestone pavement habitat for climate change

Chapter Three discusses the requisite stages of environmental assessment required in order to provide a management plan for habitats such as limestone pavements. This study has attempted to provide the basis for a management plan using this methodology however further research is required in order to provide a practical set of management guidance with which to conserve limestone pavements in the future. Future research will be advised using the discussions and conclusions of the chapters in this study using the same structure arrived at in the methodology.

8.3.1 Examine the characteristics that could make the impacts of climate change better or worse in limestone pavements.

8.3.1.1 Continued microclimate monitoring on the current sites

As indicated by the literature review, monitoring is extensively advocated to manage climate change within a limestone pavement ecosystem (Yorkshire Dales National Park Authority, 2011; Arnside & Silverdale Partnership, 2015). In order to progress the findings of this study, microclimate data should continue to be collected on the sites already in use using the methodology outlined in Chapter Four. Based on the limitations detailed in Subsection 4.4.9, it is recommended that the methodology should be adapted to more frequently change the relative humidity logging equipment to account for known flaws in the apparatus.

8.3.1.2 Expand the limestone pavement grouping system made by Willis to other countries

The ability to represent and compare limestone pavements used in this study was limited by using the limestone pavement grouping system made by Willis (2011). This was not due to a flaw in the groupings Willis created, but by the geographical coverage of the pavements Willis used. If the grouping system were to be expanded into the Republic of Ireland and other countries in the UK, it would make it possible to Group more pavements based on their uniting characteristics and conduct broader ranging research. Research such as this may make it possible to identify the elements of these Groups that may be impacted differently by climate change.

8.3.1.3 Expand microclimate monitoring

This study's scope has been limited by the budget and time available. If future monitoring were to be expanded, the recommendations made in the conclusions of Chapters Four and Six may provide further data which would develop the conclusions of this study. Chapter Four states that the current study may be expanded to explore the effect which the base of the grike has on relative humidity. This may be achieved by installing data loggers at a range of depths, following the methodology above in Subsection 8.3.1.2. In addition to these data loggers, further records of humidity could be gathered from the base of grikes at the same depth, width, orientation and site. Expanding the study of grike microclimates in this way would allow a direct comparison between humidity in the grike body and at the grike base. Providing this comparison may provide the data to expand on the zonation hypothesis proposed in this study.

In both Chapters Four and Six, it is suggested that further limestone pavements may be investigated in order to broaden the representation of any conclusions drawn from the data. From the limitations identified in these chapters, there are two ways this study may be expanded in order to have greater representation. Expanding Willis' (2011) grouping system, as proposed above, would make it possible to use a new set of Groups to launch a broader investigation of the microclimate of pavements. This new set would encompass a broader range of Groups that may provide a more representative sample which includes wooded and shallow pavements, which were not included in this study. In addition to a broader range of limestone pavements, a future study may also benefit from a broader range of climates. In chapter six, the Isle of Anglesey was identified as having a warmer microclimate than other areas from the sample. By studying the climate of further areas containing limestone pavements, it may be suggested that future investigations may be made from a broader range of climates. A future study incorporating these suggestions may more fully represent a broader range of limestone pavements and climates to provide data on which more representative conclusions may be drawn.

8.3.1.4 Progress understanding of microrefugia potential

The microclimate of a habitat is considered to be among the most important factors when identifying the suitability of a habitat to become a microrefugia in the future; however, there are other elements which contribute to a habitat's capacity to shelter species (Rull, 2009; Suggitt, 2012). This study identified qualities which protect species in grikes from severe weather; however, further research is needed in order to understand the effects which more extreme and frequent weather disturbances may have on the grike inhabitants. The data and conclusions from Chapter Four of this study may provide a starting point from which simulations of events may be generated. Further research into the potential of limestone pavement disturbance should also be continued concerning flooding from turloughs or rising sea level (Prosser et al., 2010; Naughton, Johnston, McCormack & Gill, 2017).

8.3.1.5 Develop an understanding of how non-climate pressures may interact with climate pressures

The impacts of climate change do not act separately from other threats to the wellbeing of habitats, and both climate-related and non-climate related threats may combine to create a higher level of stress (Ackerly et al., 2010). This study has not provided any further insights which may assist in understanding this connection; however, it has provided some data which may be used in studies which may improve our understanding. Prior authors have identified grazing to be crucial to limestone pavement management (Dunford, 2001; Thom et al., 2003; Willis, 2011). These identify the impacts which inappropriate grazing has on the flora of the pavements (Deenihan, Donlan, Breen & Moles, 2009; Cross, 2006) and by extension may have on the invertebrates by affecting their food source (Webb, 1961; Scottish Natural Heritage, 2013; Waring & Townsend, 2017). A greater understanding of the effects of climate change on the microclimate of grikes may be used in conjunction with what is known about the effects of grazing. In this way, a combination of these fields may progress our understanding of how these two pressures may act on grike species.

8.3.2 Develop and refine these assumptions

8.3.2.1 Model the grike microclimate

To the knowledge of the author, this study has provided the first indications of how the future temperature of the grike may be impacted by climate change. Further refinements can be made to this simulation, and newer projections of climate may be created. In Subsections 6.4.3.2, it is recommended that further refinements could be made by using more substantial microclimate data sets collected after the end of this study. In the future, as new models become available from both the EURO-CORDEX and UKCP18 climate projections, the simulation method used in this study could be refined. Further simulation and modelling could use projections with both a higher geographical and temporal resolution, making it possible to provide results for specific limestone pavement areas and simulate daily fluctuations in temperature, respectively. Further work such as this may allow land managers to reassess the conclusions of this study in light of more refined results that are made at a higher resolution for specific pavement areas, and provide data against which measurements of grike temperatures may be compared.

8.3.2.2 Compare the simulations of this study to future grike microclimates

Monitoring measures are often criticised for not being proactive and occasionally stymieing action (Heller & Zavaleta, 2009). This study has, however, provided a simulation of the grike temperature using the UKCP18/RCP8.5 climate projections, against which future monitoring may be compared. It has also been suggested that further simulations should be created and may be used in the same way. By indicating what the future microclimate of the grike may be like under different climate models; the monitoring of limestone pavement grikes can be moved forward from academically studying climate change, and progress toward informing the future management of a limestone pavement habitat (Heller & Zavaleta, 2009).

8.3.2.3 Investigate similar habitats

This study has been able to provide greater insights into the possibilities of the grike microclimate's reactions to climate change, by investigating the effects of severe weather events and the temperature of the grike in a future climate scenario. Potential future research could be conducted to investigate the similarities between the microclimate of limestone pavements in Britain and Ireland and those classified as limestone pavements in Portugal and Italy (European Environment Agency, 2013). These studies would follow the methodology proposed in Subsection 8.3.1.1 and pavements may be chosen which contain similar features to those being studied already. By investigating the microclimate and biodiversity of these pavements, it may be possible to gain further insights into the possible future of limestone pavements in Great Britain and Ireland.

8.3.2.4 Further fluid dynamics simulation

This study has explored the use of Computational Fluid Dynamics (CFD) in the field of ecology in order to produce foundational simulations to show the interaction between micro and macro climates at the air mixing boundary. In Subsection 5.4.4.2, it is recommended that the simulation used in this study could provide a starting point from which other simulations can more accurately represent the airflow within the grike. It is suggested that this could be achieved by introducing three-dimensional simulations, upstream turbulence, variable wall textures; wind velocities deduced from climate projections and investigate how windbreaks may be effective in mitigating the effects of climate change. Further CFD research may also usefully be employed to simulate the effects that scrub on pavements may have as a windbreak, and if found to be beneficial, these findings may inform future grazing practices to manage scrub. These simulations may follow the methodology used in this study with the addition of supplementary features. Simulations such as those suggested may refine the conclusions made by this study and make it possible to simulate how air mixing in the grike may be affected by climate change.

8.3.3 Consider the intrinsic importance of the grike to species

8.3.3.1 Conduct a follow up invertebrate study to more fully explore the link between microclimate and invertebrates

The survey reported in Chapter Seven identified several possible connections between the depth of a grike and the invertebrates found within it. The limitations of this chapter identified several ways in which the methodology may be improved in order to create less ambiguity in the findings. Future studies may consider pitfall trapping in addition to the vacuum sampler, as it was found that vacuum sampling may have been biased toward smaller invertebrates, whereas pitfall trapping may not be biased in this respect. Future research may consider conducting a short microclimate investigation in each of the grikes from which invertebrates are sampled, in order to more definitively make the connection between invertebrate presence and the specific grike microclimate. Future studies investigating the specific effects of microclimate on invertebrates may also conduct a study with more samples from a smaller geographical area. Based on the limitations of the current study, it may be found that this removes additional variables and provides a more substantial data set from which to make conclusions.

8.3.3.2 Monitor invertebrate life on sites where any microclimate data is gathered

Monitoring can be used to identify changes to biodiversity, pests or pathogens and changes to abiotic factors such as geodiversity and microclimate. Ward and Evans (1975) provided a baseline level of floral biodiversity from which both Margules, Nicholls and Usher (1994), and Thom et al. (2003) worked to identify deviations in floral diversity. As part of this study, invertebrate monitoring has recorded a snapshot of the invertebrate diversity found within a subset of grikes. Although it is much smaller than Ward and Evans' (1975) survey, this work could provide the grounding for similar follow-up studies to monitor invertebrate biodiversity within the base of a grike. In turn, further monitoring may establish an understanding of the interaction of species inside and outside the grike. Further monitoring may be done through repeat sampling over a wider variety of sites and using time scales that may indicate seasonal or longitudinal change. In this way, monitoring can be used to establish the existence of an invertebrate community or observe any passive and active change from the baseline set by this study (Millar, Stephenson & Stephens, 2007). Future work may be done by using the methodology for monitoring invertebrates used in this study in order to make direct comparisons between past and future results. Alternatively, future sampling may benefit from the use of pitfall trapping, in addition to vacuum sampling, as it was possible that the vacuum sampling used by this study was not capable of capturing all invertebrates present in the grikes. Based on the rapidity of change observed in the flora of limestone pavements and the rate at which climate is predicted to change over the 21st century, any future monitoring of invertebrates should be conducted with greater frequency than has occurred in the past (Margules, Nicholls & Usher, 1994; Thom et al., 2003). A wider variety of sites from which to monitor invertebrate life may be gained by expanding Willis' (2011) grouping system, as proposed in Subsection 8.2.1.2. Any new classifications would encompass a wider range of pavements and provide a more representative sample of limestone pavements as a whole.

8.3.3.2 Model species distribution to include the grike microclimate

The findings from this study and the further research advocated by this chapter will provide a foundation from which predictions may be made about the future of the grike microclimate with a higher degree of certainty than has previously been possible. In order to understand which species may find the grike to be a microrefugium, it is necessary to develop species distribution models that are appropriately scaled. These models bust be capable of capturing the microclimatic stability of the grike and matching it to the adaptive capacity of the appropriate biota found in the grike (Keppel et al., 2012).

9. Conclusions

9.1 Evaluation of the extent to which each of the aims and objectives has been met

This thesis was carried out to complete two aims:

1. Provide a detailed description of the microclimate found within the grikes on open carboniferous limestone pavements in Great Britain and Ireland
2. Identify the research which is needed in order to provide more effective guidance for the management of open carboniferous limestone pavements in Great Britain and Ireland with regard to climate change.

This subsection details the evaluation of the extent to which this thesis achieved these aims and the objectives identified in Subsection 1.3.2 of this study.

9.1.1 Establishing a robust philosophical and methodological structure for achieving the aims of the thesis.

Chapter Three provides a philosophical grounding to direct the approach of this study and the philosophical approach taken to conservation used to inform the justification for management. These philosophies ground the approach taken to achieving Aims One and Two.

The positivist paradigm provided the most effective philosophy for this research, as this underpinned the empirical nature of the research taken in order to achieve the first aim.

By acknowledging the need for conservation to prioritise conserving nature for its own sake, while also acknowledging that conservation must occur within a human-altered landscape, the conservation philosophy of this thesis has been effectively used to ground the discussion of the future research required to manage limestone pavements for climate change.

The methodological structure to this thesis took inspiration from documented approaches to conservation in the context of climate change. This structure informed the stage-wise approach of this study in order to achieve the research required to inform the second aim.

The literature review of this thesis contributed to the first objective of this thesis by discussing the lack of research investigating the effects of climate change on the grike microclimate and habitat. The lack of directly relevant research made the stage-wise approach used essential. Each phase of the methodological structure provided the foundations for the subsequent stages. While the data and conclusions were suited to the requirements of this thesis, the recommendations for future study identify areas where research is required to substantiate the conclusions of this thesis further.

Chapter three discusses the approach taken to determine the sites used in Chapters Four and Seven and discusses the validity of using Willis' (2011) groupings to provide a representative sample of limestone pavements.
Subsections 3.3.3.2 and 9.3 discuss the limitations of providing a representative sample of limestone pavements to be used in this study. However, given the limitations discussed, the method selected has fulfilled the second objective by providing a diverse group of open carboniferous limestone pavements from which to collect data in order to achieve the first aim.

9.1.2 Provide a detailed description of the microclimate found within the grikes on open carboniferous limestone pavements in Great Britain and Ireland.

The literature review of this thesis discusses the prior research conducted to understand the grike microclimate and contributes to Objective One by informing the methodology and discussions of subsequent chapters. Chapters Four, Five and Six of this thesis provided the most comprehensive description of the grike microclimate through direct observations and simulation, providing a level of detail and scope for a wide-ranging analysis and discussion of the microclimate within a grike.

By collecting data from a broad range of limestone pavements, from two countries in Britain and Ireland, this study has identified the patterns in the microclimate which are reproduced on the multiple sites studied, and identified distinctive occurrences on specific sites. The conclusions of this study can be claimed to be generalisable, with a higher level of reliability than prior studies which had a narrower extent.
The description of each of the sites in Chapter Three and the methodology for selecting grikes in Chapter Four provided a subset of grikes for study. Due to the efforts taken, this study did not face the same issues as past studies of this type, and loggers were left uninterrupted and provided over five years of microclimate data to inform the analysis of Objective Three. Prior studies informed the measurements taken to describe the microclimate of the grike and the method for collecting the data of the grike microclimate. This made it possible to draw comparisons to past studies and base critical elements of the methodology on tested and evaluated approaches. By directly measuring three closely linked measurements of microclimate which have evidence of influencing the wellbeing of invertebrates (Subsection 7.2.2.2); this study provided a level of detail which allowed for discussions of the measurements' interdependence to create a microclimate which influences the habitability of grikes.

The frequency and duration of data collection used in this study gave a level of temporal precision and breadth to describe the microclimate of the grike in greater detail than the past studies mentioned previously. The scale of the microclimatic data collected in this study permitted the use of techniques to observe the rate and delay in temperature change within the grike, and isolate periods of severe weather for closer scrutiny. The analysis that was conducted using each of these detailed data sets provided the impetus for discussion of the present and future grike habitat, which would not otherwise have had a grounding in primary data.

Temperature data were collected from grikes at 0.25m intervals, and relative humidity and light intensity data were collected at 0.5 m intervals, for grikes ranging from 1.25m to 2m depth. All three measurements were taken each metre below 2m and at the bottoms of grikes. To the author’s knowledge, this has provided the largest frequency and depths to be sampled in a grike microclimate study. By providing this spatial frequency of measurements, this study was able to give a more precise description of the stability found with increasing depth into a grike, which made it possible to hypothesis the zonation in the grike.

Data were collected from four orientations of grike, directed on and at 45° from the cardinal compass directions. In combination with the breadth of data collected, the large number of orientations of grike that this study explored provided a nuanced description of the connection between, light intensity and temperature with regard to orientation, depth and time. This analysis provided insights which allowed for a more wide-ranging discussion of variation in temperature occurring in different parts of different grikes, which allowed for the temperature to be simulated.

Simulating the airflow within a grike brought a unique element to the study of grike microclimates, and added detail to this study, which would have been unfeasible to produce outside of the virtual environment, as stated in Subsection 4.2.2.2. While acknowledging the limitations of the process in Subsections 5.4.3 and 9.3, the methodology presented a balance between representing the realities of the grike microclimate and reproducing descriptive idealised flows. This was done by grounding this study in the tested methodologies of fluid dynamics and the extensive research of prior limestone pavement investigations.

The results of the CFD simulation provided the first representation of airflow in grikes ranging from 0.2m to 4m deep, 0.04m to 1m wide and with a lip curve with a radius of 0.05m to 0.3m. Research of this type has, to the best of the authors' knowledge, not been simulated in grikes before. By representing the realistically wide range of grike forms at a frequency of 0.02m, this study has fulfilled Objective Four by providing enough detail to discuss the limitations at which types of flow develop and collapse.

The discussion of the grike microclimate was informed by detailed descriptive analysis and simulation, which used the wealth of data created by this study. This detail of analysis provided a number of new conclusions not yet observed by the author in grike microclimate research and fulfilled Objective Three and contribute to Aim One.

The products of the descriptive analysis used in this study have been mainly described in the previous paragraphs. By having a large amount of data available it was possible to conduct descriptive analysis which drilled down to describe the relationship between the grike structure and the microclimate at levels of detail that have advanced the discussions of the grike microclimate. By uncovering the variations in temperature created by the interplay of grike insolation, depth and orientation, this study provided the foundations of the subsequent simulation to understand the physical basis of these features of the grike. By calculating the angle of incidence and the limits placed on direct insolation within the grike, this simulation has progressed the discussions of Burek and Legg (1999), and Alexander Burek and Gibbs (2007).

This study has made it possible to create a simulation of the grike temperature based on external temperature, the month of the year and the grike's depth and orientation, using the research conducted in Chapter Four. The linear regression used in the simulation was identified to be the most effective, and most accurate of those tested when evaluated using the k-folds cross-validation method. The simulation which has been produced had been shown to recreate a number of the characteristics of the grike microclimate with regard to depth and seasonal patterns. This simulation has provided a quantitative understanding of the grike temperature and enabled discussions of the grike's present and future temperature based on a degree of statistical probability.

By applying the methods of data collection and descriptive analysis detailed in this subsection, this thesis has provided a detailed description of the microclimate found within the grikes on open carboniferous limestone pavements in Great Britain and Ireland.

9.1.3 Identify the research which is needed in order to provide more effective guidance for the management of open carboniferous limestone pavements in Great Britain and Ireland with regard to climate change.

The discussion in Chapter Eight and each of the systematic chapters of this thesis evaluates the evidence provided by this study in order to fulfil Objective Eight by identifying several options for research which may be required in order to manage the limestone pavement habitat in Great Britain and Ireland for climate change.

In the literature review to this thesis, the current and potential threats to limestone pavements were discussed, and the methods for the management of habitats for climate change were evaluated, which fulfilled aspects of the first objective. This chapter identified that the impacts of climate change are not merely increasing temperatures, but multiple threats which act in conjunction with existing habitat pressures (Travis, 2003).

By providing a detailed analysis of grike microclimates in Chapter Four, this area of the thesis contributes to Objective Three by using a data set extending for over one year. The findings of this research provide the beginnings of what is intended to be a more extensive study of grike microclimates, as outlined in Subsection 8.3.1.1. Improvements to the current method have been identified in Chapter Four and incorporated into the recommendations for future research. The methodology outlined in Chapter Three identified that this study's scope to represent all limestone pavements in Great Britain and Ireland was limited by selecting Willis's classification system for grouping pavements. While this method served the purposes of this study, expansion of this grouping system to include a broader range of pavements was identified as a possible avenue for research. By expanding this grouping system, commonalities between pavements may be applied more widely furthering, the aim of Willis's thesis, to compile management guidelines related to pavement classification (Willis, 2011). Further limestone pavement classification and the conclusions of Chapters Four and Six of this thesis provide the starting points with which to identify the pavements on which further microclimatic study may take place. Subsection 3.3.1.3 identifies that by expanding the microclimate research carried out by this study to more pavement Groups and more varied climates, a more representative impression of the grike microclimate may be gained.

Chapter Eight explores the potential for the limestone pavement grike to be considered a microrefugium, fulfilling the seventh objective of this study by using the findings from preceding chapters to place the roll of the grike in the context of future climate change. Subsections 8.3.1.4, 8.3.1.5 and 8.3.3.2 describe research which may be carried out in the future in order to progress this objective. Research from the literature review suggests that microclimate is important in the identification of refugia (Suggitt, 2012). An understanding of the disturbance from new and existing threats and the potential for species to adapt to climatic changes are also required for the further management of refugia for climate change (Keppel et al., 2012). Chapters Four and Six provide elements which may contribute to finding the answers to these questions by providing some of the first studies of the effects of severe weather and climate change conditions on the grike microclimate. Chapter Seven may also provide some of the first insights into species distribution in the grike by identifying the larger diversity of invertebrates found at the bottom of deeper grikes.

Chapter Five simulated the air circulation in the grike and fulfilled Objective Four by contributing to the understanding held about how the form of the grike influences these flows. This chapter provides the foundations for future work, which are outlined in Subsection 8.3.2.4, where further developments to the existing simulation are proposed. The limitations of Chapter Five detail the restrictions placed on the simulation used in this study, which impacted the representativeness of the results. The future research which is suggested rectifies these restrictions by identifying more realistic flow physics and speeds, and more realistic three-dimensional geometries with texture. It is also suggested that airflows should be based on the predicted impacts of climate change. By deriving these suggestions from work carried out in Chapter Five, it is possible to use the research from this thesis as a starting point for future CFD simulation.

In chapter six, a preliminary modelling exercise was described, which fulfilled Objective Five by providing a temperature simulation of the future grike microclimate. The simulation conducted as part of this thesis has provided valuable data and insights which may go on to guide the future research suggested in Subsections 8.3.2.1 and 8.3.2.2. By simulating the present and future temperature of the grike, Chapter Six has provided the starting point for future simulations to be conducted. This may be achieved through the continued collection of microclimate data from grikes suggested in Subsection 8.3.1.1. This continued data collection may also serve as a comparative data set for the available simulation and future iterations, in order to understand if the temperature in the grike is progressing as expected. Future simulations may also be advanced by using the limitations of chapter six, which identified that further modelling should use a broader range of climate projections from a more granular resolution when they become available.

Chapter seven details a descriptive survey of the invertebrates in the grikes of limestone pavements that were studied. This Chapter completed Objective Six by contributing to the knowledge of how invertebrates are distributed over the depth of a grike. This survey offers the foundations for future studies suggested in Subsection 8.3.3.1 and 8.3.3.2, by providing the possible first sample for follow up studies following a similar or modified methodology. Future investigation of the connection between grike invertebrates and microclimate may be modified to reduce ambiguity in the conclusions of this study, by modifying the methodology of this survey based on the limitations which were found in Chapter Seven. Future invertebrate monitoring may use the methodology used by this study in order to create comparable results or modify the methodology based on the recommendations arrived at in chapter seven.

Chapter eight has acknowledged the conclusions and limitations of this study, and the research of other authors on the subject of climate change, microrefugia and habitat management. In this way, Chapter Eight has achieved the completion of Objective Eight of this thesis by suggesting future research which may provide guidance to inform future management of the open carboniferous limestone pavement habitats in Great Britain and Ireland.

9.2 Key findings and contributions made to the field of limestone pavement conservation

Full details of this study's conclusions can be found in the "conclusions" subsections of each of this thesis' chapters. The following summaries provide the contributions which have been made by this thesis to advance the knowledge of limestone pavement microclimate and fauna.

9.2.1 Zonation in the grike

Chapters Four, Five and Seven have produced conclusions which identify possible zones within the grike. The upper zone above 75cm is characterised by shelter from the surrounding clints, but is most exposed to the macroclimate and is most changeable. The character of the lower zone below 100cm is more stable than the upper zone, possibly due to the reduced influence of the macroclimate and the greater influence of the limestone surrounding the grike. The transition zone between 75cm and 100cm is characterised as being influenced by smaller amounts of destabilisation than the upper zone and may be less influenced by the surrounding limestone than the lower zone.

9.2.2 Key microclimate findings

From the findings of this thesis, further evidence has been gained to confirm the hypothesis that greater stability is found with depth into a grike. The evidence was gained through the observation and simulation of temperature, light intensity, relative humidity and airflow; and have led to the following conclusions. The simulated airflow in a grike developed a vortex at the surface which was mostly constrained to a depth equal to the grike width. This meant that a hypothetical vortex was limited to the upper zone for all grikes in the long term microclimate study. Below the vortex, air currents became weaker and less turbulent with depth, which resulted in a possible lesser degree of destabilisation in the lower zone for the grikes in the long term microclimate study. The aspect ratio and lip curve influenced the vortex formation within a simulated grike such that a grike with aspect ratio W/H=3.33 had no vortex within it, and a small curve to the simulated grike lip could reduce the integrity of the vortex. Most of the insolation from the sun was limited to the upper zone of the grike. The grike's orientation affected the time of day when direct insolation penetrated deeply into the grike. This impact was such that in the north to south orientated grikes the sun penetrated most deeply at midday, and in any east to west orientated grike the most deeply penetrating insolation was found at either end of the day.

The larger effects of insolation and airflow at the surface of the grike are hypothesised to affect grike temperature. This effect may be the source of the more rapid rate of temperature increase recorded in the upper zone of the grike when compared to the rate of temperature decrease. Solar heating on differently orientated grikes had a nuanced impact on the temperature at different depths of the grike. The thermal mass of limestone surrounding the grike is hypothesised to have had a stabilising effect on the temperature of the air in the grike. This stabilisation was such that over the summer in the lower zone of the grike, the temperature decreased more rapidly than it increased. The greater effect of insolation and airflow at the surface of the grike may have reduced the relative humidity at the grike surface. The relative humidity in the grike was not as distinctly zoned as other microclimatic variables; however, it was found that humidity was increased close to the grike bottom.

By collecting data for over five years on five sites, this study has produced the longest continuous set of grike microclimate data from the broadest range of limestone pavements known to the author. The evidence gained from collecting this data has led to the following conclusions. The effect of the geographical location had a greater impact on the microclimate of a grike than Willis' (2011) limestone pavement Group. Temperature inversions occurred in the spring where the temperature in the upper zone was higher than in the lower zone, and the opposite occurred in the autumn. The time delay between surface heating and temperature increase within the grike has been quantified and shown to increase during the summer. The severe weather events which took place throughout the data collection provided the first observations known to the author, of how severe heat, cold and precipitation affect the grike microclimate.

The extended duration of the microclimate study has allowed for the grike temperature to be simulated. The simulation used linear regression to provide an initial relationship between the temperature in the grike and multiple other variables. This simulation provided the hypothesis that temperature will increase less rapidly inside the grike than outside; however, an increase in temperature is inevitable at all depths when given enough time.

9.2.3 Key biodiversity findings

By using vacuum techniques which to the best of the author's knowledge are new to grike ecology and by sampling invertebrates from a wide range of limestone pavements used for microclimate research, it has been possible to make the following conclusions. There is evidence to suggest that species of invertebrate predominate in different depths of grike; however, these depth ranges are not as clearly defined as was found in plants by Silvertown (1982). Using the Shannon Diversity Index, it was observed that the species diversity is moderate from 20cm to 50cm into the grike, relative to other depths. The diversity then decreases beyond 50cm until 100cm where it increases once again to higher levels than anywhere else in the grike before reducing again. There was found to be a significant positive correlation between the number of invertebrates per sample and the depth of grikes. This evidence from Chapter Seven and the connection between depth and the stability of microclimate suggested in Chapters Four and Six, are the basis for several hypotheses connecting invertebrate sample number and diversity with microclimate.

If the simulations of the future grike temperature are born out by further research and the connection between microclimatic stability and number of invertebrates is confirmed, it may be that the future microclimate of the grike remains sufficiently stable to be considered as a potential microrefugia under climate change.

9.2.4 Key methodological contributions

This study contributed to the breadth of tools used to collect and analyse data used in the study of limestone pavements. To the author's knowledge, it is the first time the following have been applied to the study of grike microclimates or grike ecology.

1. The microclimate of the grike was observed for over a year using remote monitoring technology.
2. Dynamic time warping was used to analyse the delay in temperature change between the surface and the grike.
3. Computational Fluid Dynamics was used to simulate and visualise the airflow within grikes.
4. Linear regression was used in order to quantify the effects of different variables on the grike microclimate and provide a plausible scenario of the temperature expected in the grike.
5. Vacuum sampling was used within a grike to reach the invertebrates found within areas inaccessible to other sampling techniques.

Use of vacuum sampling was considered particularly innovative as part of this study because it has allowed the first samples of invertebrates from the bottom of deeper grikes and the first use of this tool in an unobserved environment known to the author. Use of this tool provided the means to identify the changes in diversity in different depths of the grike, which was a valuable addition to this study. By allowing access to sampling from this region of the grike, it may be possible that more may be known about this unseen area of the grike and presents the possibility that the grike may contain species not yet known to science. Future use of this tool will be an asset in the continued understanding of the effects of climate change on the grike habitat as continued samples may make it possible to monitor the changes in species found in the grike over time.

9.3 Limitations of this thesis

Full details of this study's limitations can be found in the "limitations" subsections of each chapter. This chapter provides an account of the limitations underlying the entire study.

9.3.1 Representation of limestone pavements in Britain and Ireland

By working within the constraints of the methodology of this study, a degree of representativeness was sacrificed. Willis' (2011) limestone pavement groupings were used as a basis for selecting the sites and grikes on which microclimate and invertebrate data were collected. Subsection 3.3.3.2 discusses the limitations to using this methodology but concludes that it presents the most effective method of selecting a diverse set of sites from Great Britain. As no such grouping system existed in the Republic of Ireland, the sites were selected to represent extremes of character found on The Burren. In addition to the selection criteria mentioned, high priority was given to sites where the equipment would be safe and which could be accessed frequently for repeat collections. This ensured that multiple data sets from over five years were available for study. By using selection criteria which prioritised collecting a diverse and long-term data set, a degree of generalisability was sacrificed. This study has shown that while each site retains a number of characteristic microclimatic and faunal characteristics, the trends in the data show similarities. If this study had included a broader number of limestone pavements from a more inclusive area, more unique characteristics might have been identified. However, given the limitations to collecting the long term data set used, this study has provided a robust data set from which to draw meaningful conclusions. The nine $60km^2$ squares from which climate projections were sourced represent most of the limestone pavements in Britain and Ireland. If all $60km^2$ squares containing limestone pavements were included in the analysis, a larger number of coastal climates would have been sampled, which are atypical for most limestone pavements. By sampling only the larger clusters of limestone pavements, there was inherently lower confidence with which predicted effects were be claimed for sites outside the sample areas.

9.3.2 Realism of simulations

When creating a simulation, there is a compromise between realism and idealism (Savory, Perret & Rivet, 2013). Several simulations were created as part of this study, which may be improved upon in future.

The temperature simulation created as part of this study was not able to account for several aspects of the microclimate which were found to be of importance to the grike. The temperature simulation did not take into account any zoning, which is hypothesised to be important in the identification of a microrefugial grike. The simulation created in this study could not account for the delayed temperature change that as observed between the surface and the base of the grike. These limitations were introduced due to the temporal resolution of the simulation, as discussed in Subsection 6.4.3.1. The simulation used was, however, the best fitting and most accurate of those trialled and may be improved upon in future studies.

Subsection 4.2.2.2 discusses airflow within grikes as a possible physical dimension of the grike microclimate to be measured; however, this was dismissed as the equipment needed would be too bulky. Chapter Five discusses the use of CFD to recreate the grike environment and the limitations of using a technique new to grike study. The simulations were conducted in two dimensions, thus limiting the amount which can be interpreted for a three-dimensional structure. The simulations used idealised wind-speeds and flows, and this allowed for ideal skimming flows to be observed in the grikes that may not be as fully established in stronger and more turbulent flows. This chapter provides the foundational research needed to indicate the flows which were possible within the grike environment; however, further study is needed to explore more realistic flows.

The absolute temperature data available from the UKCP18 projections were limited to values for only the high emissions scenario (RCP8.5). The restricted availability of data impacted the simulation that was created as part of this study and decreased the capacity of the simulation to view the impacts of a less change in the climate of lower magnitude.

9.3.3 Use of new techniques not yet attempted within grike research

In many areas of the study, the methods that were used were not common practice in the field of grike research. As such, they were either required to begin from a more rudimentary stage or encountered technical issues which may have impacted the results. The methodology for the simulations employed as part of this study was based on the simulation of street canyon research. This research was the first study known to the author to employ CFD to the grike environment. Entering into a new area of research meant that the CFD in this study was foundational. As foundational research, this study forfeited an element of realism to limit the complexity of the simulation. The limitations of this are discussed above in Subsection 9.3.2. Although a number of other authors have studied the grike temperature, relative humidity and light intensity, this study provides the longest period of grike microclimate data collection known to the author. Prior authors have identified the possibility of faults in remote climate monitoring. Measures were taken in this study in order to avoid the known limitations of past studies. Despite these precautions, faults in some equipment were identified. It was found that the technology that was currently available for recording the relative humidity from remote locations was not yet capable of measuring small fluctuations in relative humidity in environments which are close to saturation. This limitation resulted in some failure of the equipment that was used in this study, but due to the precautions taken, conclusions could still be drawn from the data collected.

This study was the first study known to the author, to extract invertebrates from the base of grikes using a vacuum sampler. Subsection 7.4.5.1 discusses the potential of this method to extract invertebrates not always found at the bottom of the grike and may have preferentially sampled smaller grike invertebrates (Merrett & Snazell, 1983). The implications of using this method may have skewed the results toward selectively sampling smaller invertebrates, as evidenced by the lack of Carabidae that were sampled from grikes in which they may have been expected to have been present (York, 2009).

9.4 Recommendations for Further Study

Full details of the recommendation for further study can be found in Subsection 8.3. This chapter provides a summary of future research for each element of the study.

9.4.1 Continued investigation of the grike microclimate

The phenomenon of increased relative humidity found at the bottom of a grike could be investigated by collecting further relative humidity data from a range of similarly oriented grikes of different depths located at the same site.

The microclimate data collection conducted as part of this study should be continued for further years with a modified methodology based on the limitations of this study. It would be advantageous to expand data collection to include a site on the Isle of Anglesey due to the higher mean temperature projected to be experienced by this site in the future. Further sites may also be added to the microclimate study by expanding Willis' (2011) groupings to further pavements outside the scope of Willis' original study. These recommendations are discussed further Subsection 8.3.1.

9.4.2 Further simulation and modelling

Further refinements to the simulation created as part of Chapter Six should be conducted. These refinements include the use of finer-grained modelling on individual limestone pavements using 12km^2 grid squares, to provide more explicit recommendations for specific limestone pavements. The simulation created in this thesis could also be refined by trialling variables such as the zones created as part of this thesis, using newer data collected as part of the monitoring previously recommended and modelling severe weather events with higher frequency and intensity. Data from the temperature simulation from this and future studies may also be used in combination with microclimate monitoring, to understand whether the grike temperature changes as expected. In order to progress the discussion of grikes as a microrefugia, future research may conduct species distribution modelling incorporating what has been found in this and the proposed studies.

Further simulations could also be conducted using fluid dynamics. Any further investigations may use this study as a foundation, but incorporate three dimensions, textured walls, windbreaks, and varied wind-speed and turbulence into the simulations. These further simulations may be progressed toward using predicted environmental variables for different regions under climate change. Research into how surface flora act as windbreaks, may also prompt further research to identify the potential future role of scrub on limestone pavements and its's management through grazing. These recommendations are discussed further Subsection 8.3.2.

9.4.3 Further investigation of invertebrates within the grike

In order to investigate the linkage between microclimate and invertebrate populations more closely, a dedicated study could be conducted by sampling both microclimate data and invertebrates from the same grikes using a range of sampling techniques.

It may also be beneficial to monitor the number of invertebrates found within limestone pavement grikes in the future. A possible methodology may be based on that used in this study, but incorporate lessons learned from the limitations in Chapter Seven. These recommendations are discussed further Subsection 8.3.3.

9.4.4 Further understanding microrefugial potential

This study was able to provide more insight into the potential of the grike microclimate to respond to climate change by investigating the effects of severe weather events and future climate scenarios. Potential future research could be conducted to investigate the similarities between the microclimate of limestone pavements in Britain and Ireland, and those classified as limestone pavements in Portugal and Italy (European Environment Agency, 2013). By investigating the microclimate and biodiversity of pavements in warmer countries, it may be possible to identify whether these habitats are currently providing refugia for species found in grikes in Great Britain and Ireland.

Although research suggests that microclimate is important for the establishment of a microrefugia (Ashcroft, 2010), the impacts of climate change do not act in isolation of other threats to limestone pavements, such as inappropriate grazing and human disruption. Further research may be conducted to understand how the most pressing non-climate threats may be exacerbated or diminished by the impacts of climate change identified in this and further studies.

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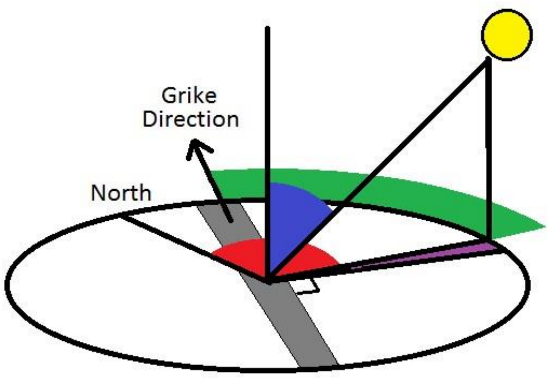
Appendix 1

A1.1 A theoretical approach to modelling light within a grike

The angle of light striking the grike wall is the product of the wall angle and solar altitude angle, which is affected by season, time and geographical position. The light which enters the grike is however limited due to the size of the grike mouth and the shadow cast by the grike walls having a limiting effect on radiative heating in the grike.

For this reason, a model has been created to predict the length of time the sun shines into different levels of the grike. These predictions are based on the location, orientation and width of the grike, and also the angle of the sun. By using trigonometry, it has been possible to ascertain the depth of penetration at any time of day.



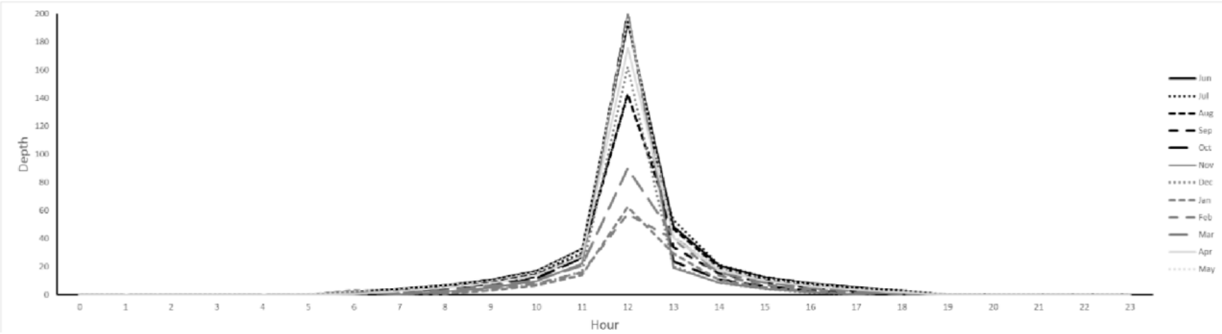
Raw data was gathered from the solar angle calculator provided by the National Oceanic and Atmospheric Administration. By using the time, date and geographical position, it is possible to provide the surface incidence angle (blue) and azimuth angle (red) (Figure A1.1.).

Figure A1.1Demonstration of solar angle

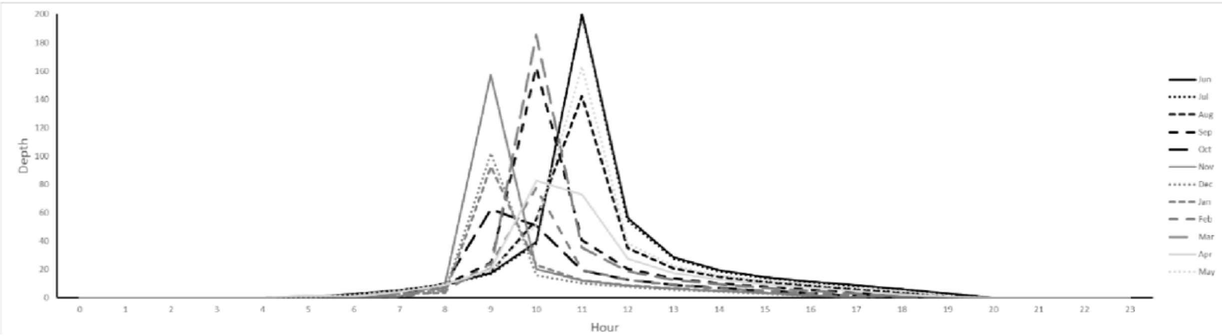
The basic environmental data were gathered for one year based on the location on the Fanore pavement. This data were modified to give the azimuth angle from the orientation of the grike (green) to allow for the different ordinations of grike to be modelled. The azimuth angle was further modified to give the angle from 90° to the grike in both directions (purple). By using the cosine of this angle and a hypothetical grike width, it is possible to calculate the distance the light beam travels in the x plane before it hits the grike wall. By using this measurement and the tangent of the surface incidence angle, it is possible to calculate the length of the beam before it hits the grike wall. It is then possible to calculate the depth the light beam travels in the y plane; this figure is limited by the hypothetical depth of the grike. By using this system, it is possible to calculate the duration of time light reaches different depths.

A1.2 Light Modelling

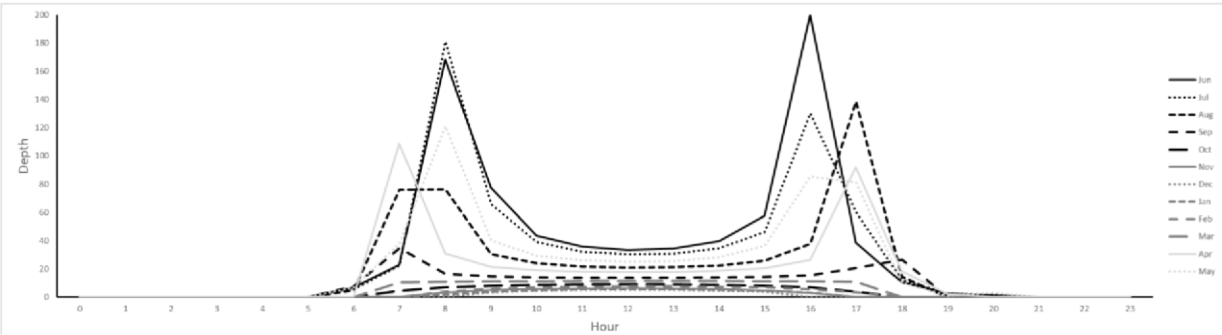
As has been discussed, light has been modelled using trigonometry to ascertain the amount of time light reaches the various depths of a grike. A model of a hypothetical grike of width 20 cm and depth 200 cm was used to identify a number of scenarios.



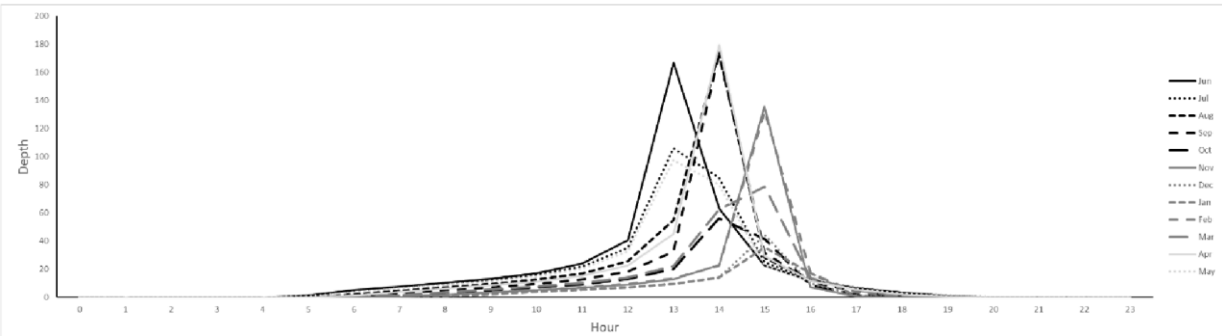
(a) North-South



(b) NE – SW



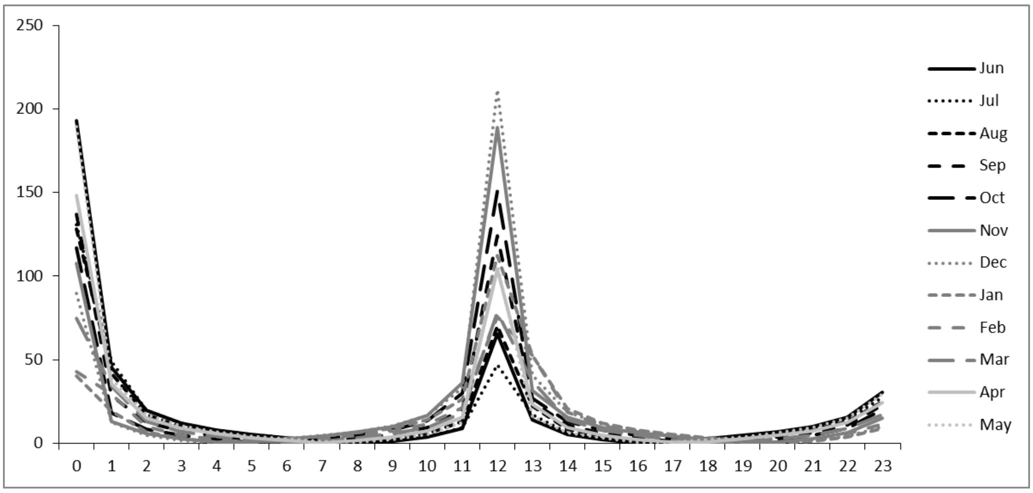
(c) East – West



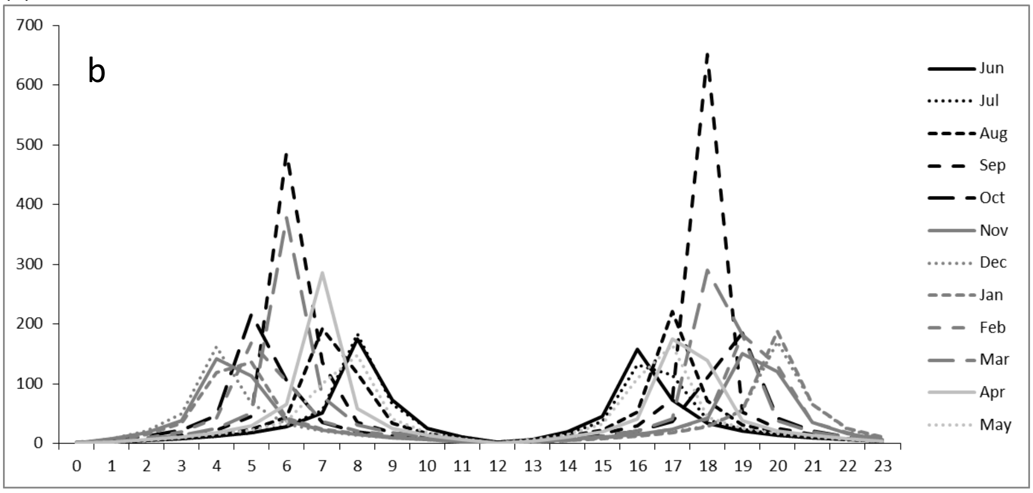
(d) NW –SE

Figure A1.2 Simulated depth of an unbroken light beam in grikes of various orientations over the course of a day

Figure A1.2 shows the depth of a light beam in a hypothetical grike, as the orientation of the grike changes the hour of peak light depth changes also. The depth given is the depth before the beam hits a grike wall or floor but gives no indication of the distance travelled before the depth recorded is gained. figure A1.3 provides the distance that an unbroken beam of light would have to travel in order to reach the depth described by figure A1.2.



(a) North – South



(b) East – West

Figure A1.3 Distance travelled by a beam of light over the course of a day on the x-axis for a grike orientated.

Figure A1.3 shows that in summer, the light must travel only a relatively short distance on the x-axis to hit a wall or floor of the grike; however, in winter, this distance increases. This is especially the case for light entering the EW grike. The distance travelled on the x-axis gives an indication of the likelihood that a beam of light will be interrupted as there is an inverse relationship between distance and probability of interruption.

Figure A1.4 shows the angle of light from the vertical, indicating the intensity of light when it hits the grike floor or the grike wall.

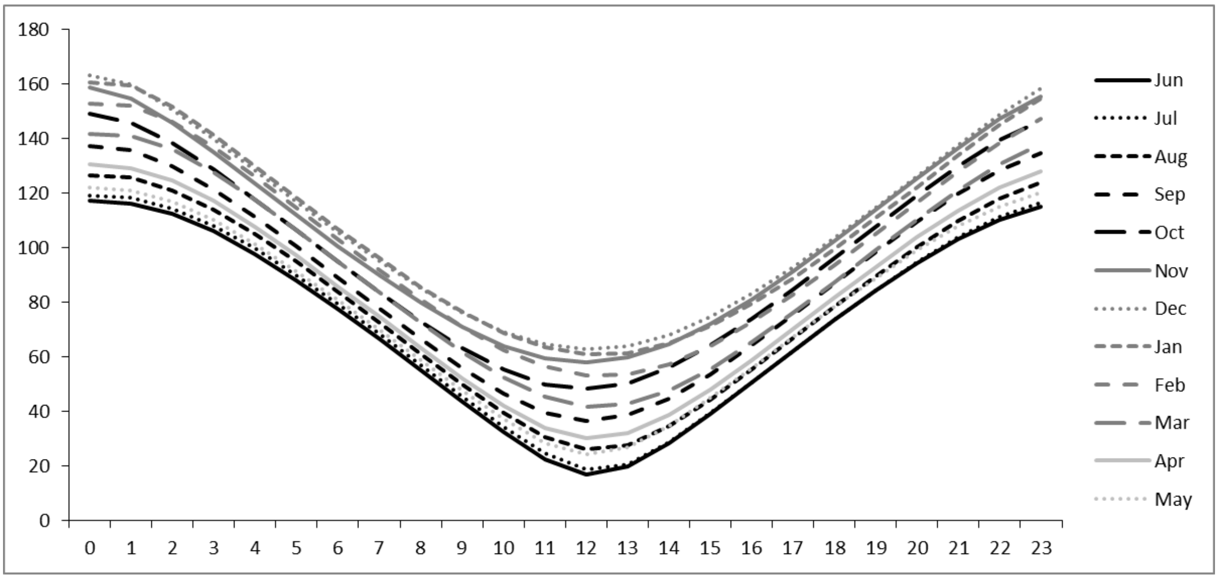


Figure A1.4 The angle of sunlight from the vertical over the course of a day for each month of the year.

Figure A1.4 shows that the angle of the sunlight rapidly changes over the course of a day in both summer and winter. The difference is that in winter the angle of the sun starts much lower than in summer so maintains a lower profile over the course of the day. During summer the peak angle of the sun is 16° at midday (where 0 would be directly overhead) when compared to winter this is 48° higher, creating much more intense heat on impact with the ground. figure A1.4 also shows that during summer, the sun is above the horizon (90°) for a greater period of time. In winter the sun is above the horizon for only around 9.5 hours compared to 15 hours in summer.

A1.3 Daily solar intensity cycles

North-South

In the NS grike (Figure A1.5), it is possible to see a distinct peak focused just after mid-day. This is extremely close to the predicted peak light depth in figure A1.2 and predicted peak light distance along the x-axis in figure A1.3. The discrepancy in the timing of this peak can be explained by the slight tendency of the grike toward the west. figure A1.2 predicts that the light will penetrate to 25 cm from around 11:00 to 13:00. This coincides with the increase in light intensity in figure A1.5 a considering a margin for error due to the slight difference in orientation.

Figure A1.5 b shows that the 125cm deep NS grike has higher light intensity than a similar EW grike in figure A1.6 b, but only during winter. Figure A1.2 shows that direct light from the sun permeates deepest in the NS grike during winter.

East - West

The depth reached by a beam of light in an EW grike is very different from an NS grike. There are two peaks in light depth, and these vary in time with the season. At the height of summer, the peak in depth is at 8 am and 4 pm. The time of peak depth spreads out from midday as the date nears the winter solstice. Figure A1.2 shows that direct light from the sun extends past 25cm for only six months of the year and passes 100cm for only four months. Despite the restricted reach of direct light, light impacts the grike wall for a considerably longer period of time than in the NS grike. The EW Fanore grike in figure A1.6 also shows similarities with the model in figures A1.2 and A1.3, however, because light intensity is highest during the middle of the day (as predicted by figure A1.4) the true peaks in light are closer to midday than predicted by just direct light modelling. The peaks in light intensity in figure A1.6 are also later than would be predicted by the model because the EW grikes of the Fanore pavement were not perfectly aligned to EW. During the months without distinct peaks, the shallow dome shape of the Fanore light graph is similar to the x-axis model in figure A1.2.

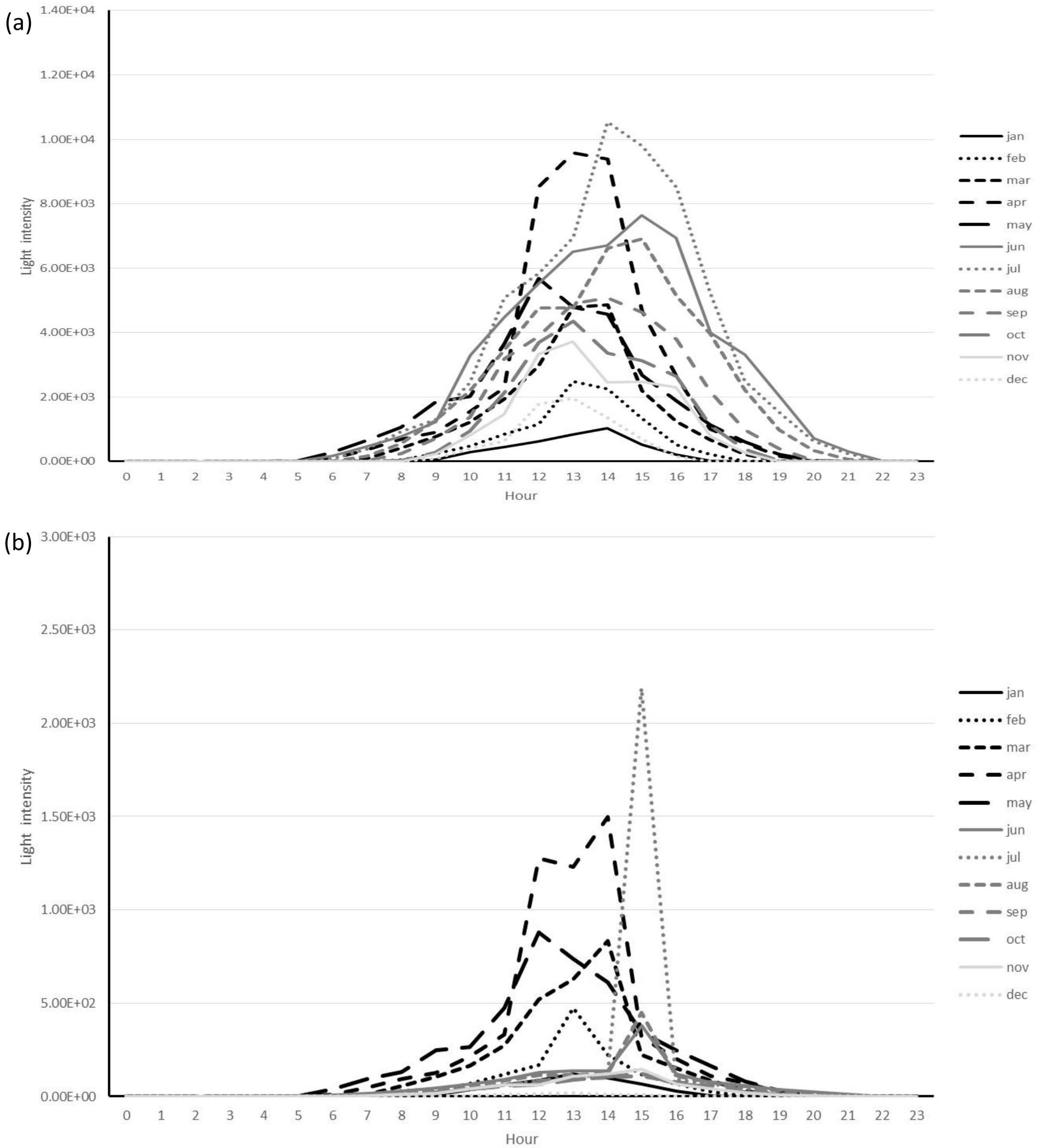


Figure A1.5 Light intensity recorded at 25cm (a) and 125cm (b) depth in a North-South orientated Fanore grike over the period of January 2012 to December 2012.

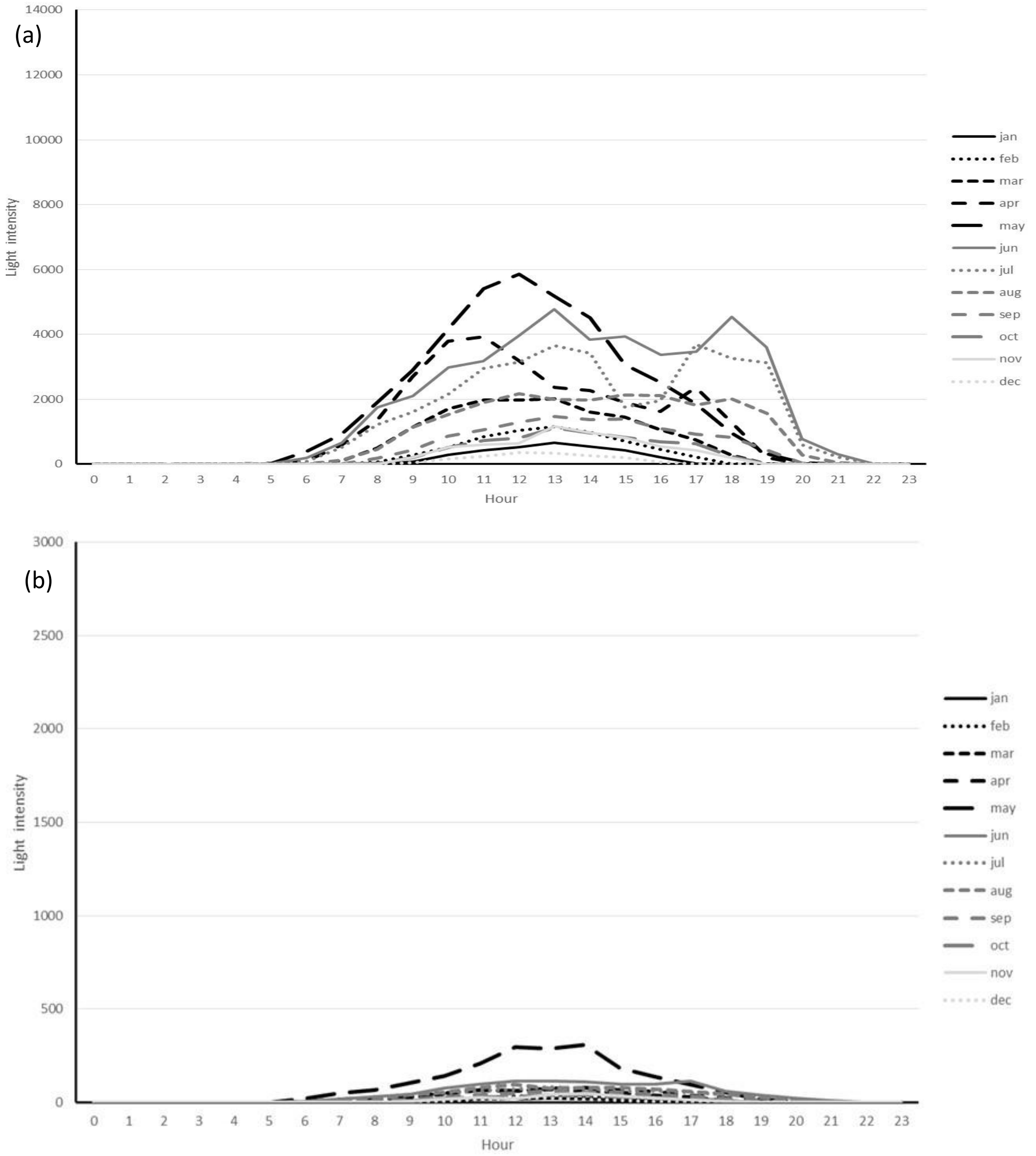


Figure A1.6 Light intensity recorded at 25cm (a) and 125cm (b) depth in an East-West Orientated Fanore grike over the period of January 2012 to December 2012.

Appendix 2

Northwest England

https://ukclimateprojections-ui.metoffice.gov.uk/wps/Execute?Request=Execute&Identifier=LS2_Subset_01&Format=text/xml&Inform=true&Store=false&Status=false&DataInputs=TemporalAverage=mall;Area=bbox|308804.17|463020.85|416804.20|571020.85;Collection=landgcm;ClimateChangeType=absolute;EnsembleMemberSet=landgcm;DataFormat=csv;TimeSlice=2020|2100;Variable=tas&ApiKey=wrM3yT2rglwmsHek8B3OIHnVDqhHN5c

North Wales

https://ukclimateprojections-ui.metoffice.gov.uk/wps/Execute?Request=Execute&Identifier=LS2_Subset_01&Format=text/xml&Inform=true&Store=false&Status=false&DataInputs=TemporalAverage=mall;Area=bbox|246846.53|351954.87|290624.32|392177.09;Collection=landgcm;ClimateChangeType=absolute;EnsembleMemberSet=landgcm;DataFormat=csv;TimeSlice=2020|2100;Variable=tas&ApiKey=wrM3yT2rglwmsHek8B3OIHnVDqhHN5c

Burren

https://ukclimateprojections-ui.metoffice.gov.uk/wps/Execute?Request=Execute&Identifier=LS2_Subset_01&Format=text/xml&Inform=true&Store=false&Status=false&DataInputs=TemporalAverage=mall;Area=bbox|-84042.36|373336.81|-75597.91|381114.6;Collection=land-gcm;ClimateChangeType=absolute;Variable=tas;DataFormat=csv;TimeSlice=2020|2100;EnsembleMemberSet=land-gcm&ApiKey=wrM3yT2-rglwmsHek8B3OIHnVDqhHN5c

Leitrim and Roscommon

https://ukclimateprojections-ui.metoffice.gov.uk/wps/Execute?Request=Execute&Identifier=LS2_Subset_01&Format=text/xml&Inform=true&Store=false&Status=false&DataInputs=TemporalAverage=mall;Area=bbox|-14391.63|452458.35|13163.88|519125.0;Collection=land-gcm;ClimateChangeType=absolute;Variable=tas;DataFormat=csv;TimeSlice=2020|2100;EnsembleMemberSet=land-gcm&ApiKey=wrM3yT2-rglwmsHek8B3OIHnVDqhHN5c

Appendix 3

Descriptive statistics for each site

A3.1 Holme Park Quarry

Holme Park Quarry is a Group 3 pavement found near Holme in Cumbria in the centre of an aggregate owned quarry. There were a total of 484 invertebrates counted at this site from 22 species (all the species lists can be found in appendix 4).

<u>Phyla and Species</u>

- There was one Collembola captured on this site, but it was too damaged to identify fully.
- 96.24% of all species found were from the Mollusca Phyla. 82.86% of Mollusca species found on this site were round snails, and 17.14% were cone snails.
- Among the round snails collected, the prominent species were *Punctum pygmaeum* (41.62%, 159 counted), *Lucilla singleyana* (6.54%, 25 counted), *Discus rotundatus* (4.45%, 17 counted) and *Vitrea contracta* (3.14%, 12 counted).
- Of the cone snails, 20.25% (16) were juveniles, and the same amount were too damaged to identify, the only notable cone snail species *Lauria cylindracea* made up 54.43% (43) of those counted.
- There were very few woodlice identified on this site; two were partial specimens, one was identified as *Porcello scaber* and one as *Armadillidium vulgare*.
- The only other invertebrate found in the samples was a hunting spider. However further identification was outside the scope of this study

A3.2 Dale Head

The Dale Head site is a Group 6 pavement situated on an exposed rocky outcrop in the Yorkshire Dales. The total invertebrate count for this site was 447 individuals and 46 different species.

Phyla and Species

- On this site, 3.80% of the invertebrates were collembola (springtail). It was not possible to identify the samples further in the capacity of this study.
- 86.23% of invertebrates sampled were from the Mollusca Phyla. Of the Mollusca, 67.02% were round snails, and 32.98% were cone snails
- Among the round snail species identified *Discus rotundatus* and *Punctum pygmaeum* were counted 35 and 33 times respectively, and *Lauria cylindracea* and *Carychium tridentatum* were counted 33 and 24 times among the cone snails.
- 3.80% of the invertebrates identified were Oniscidea (Woodlice) the most common among these was *Oniscus asellus* counted eight times. 6.94% were categorised as "other".
- In the "other" category, the largest number of invertebrates were ticks.

A3.3 High Folds

High Folds is a Group 1 pavement found high above the Malham Tarn FSC centre on an area populated by sheep, surrounded by tussocky grassland. Here a total of 241 individual invertebrates were counted made up of 43 different species.

Phyla and Species

- The number of collembolan individuals found on this site made up 8.3% (20) of the total species found. Many were too damaged to identify fully. However, nine are believed to be a species of Folsomia.
- Invertebrates on the site were found to be made up of 62.66% from the Mollusca Phyla, of these 72.85% (110) and 27.15% (41) of round snails and cone snails respectively.
- Of the round species, 34.69% (38) were juveniles, 36.73% (18) were *Punctum pygmaeum,* and 10% (17) were *Discus rotundatus*. Of the cone snails, there were 29.27% (12) juveniles, 36.73% (15) and 24.39% (10) were *Columella edentula*, and no other species numbered above 10 individuals.
- There were five species of woodlouse making up 6.22% (15) of all invertebrates found and a number of "other" species making up 22.82% (55).
- There were a large number of ticks (13 counted) and unidentifiable worms (19) found on the site.

A3.4 Fanore

Situated very near the coast, the Group 3 pavement of Fanore is a hillside site surrounded by similar pavements and grassland. Here, a total of 367 invertebrates were counted and only 14 different species.

Phyla and Species

- No Collembola species were found on this site.
- Most species found on the site were round snails amounting to 87.10% (108) of all individuals whereas 10.48% (13) were cone snails.
- Of the invertebrates found on Fanore 99.18% were from the Mollusca Phyla, of these 91.48% were round snails and 8.52% were cone snails
- The round snails found were mostly *Punctum pygmaeum* and *Pyramidula pusilla* amounting to 52.78% (57) and 17.59% (19) of all round snails found respectively. There were 12.04% (13) round snail juveniles found
- The cone snails found included eight *Lauria cylindracea* and two *Carychium tridentatum*
- Two unidentifiable fragments of woodlouse were found on this site and one fly species.

A3.5 Turlough More

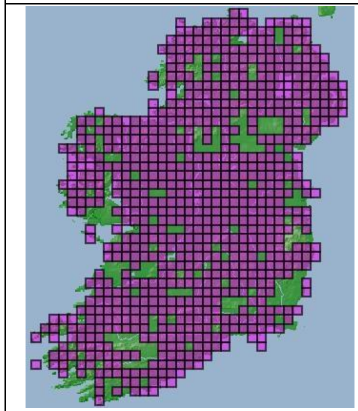
The Turlough More limestone pavement is found on the edge of The Burren far inland from the coast and contains many deeper grikes; however, due to the limitations of the equipment a maximum depth of 200cm was reached. This site contained most invertebrates with 1711 individuals counted from 25 species.

Phyla and Species

- Like the other Irish pavement, no Collembola were found.
- There was a large number of the Mollusca Phyla in the grikes of the Fanore pavement making up 99.41%, of these round snails made up 98.18% of all invertebrates (1670) and 1.82% were cone snails.
- Round snails were mainly *Punctum pygmaeum* making up 44.97% (751) of the total, and *Pyramidula pusilla* made up 26.59% (444).
- On this site, there were also a large number of damaged fragments from 130 snails (7.78%)
- The grikes on this site contained unidentifiable fragments of five woodlice and whole specimens of one *Oniscus asellus* and two *Armadillidium vulgare*.
- As well as snails and woodlice, a species of money spider was found and one Yellow Meadow ant (*Lasius flavus*).

Appendix 4

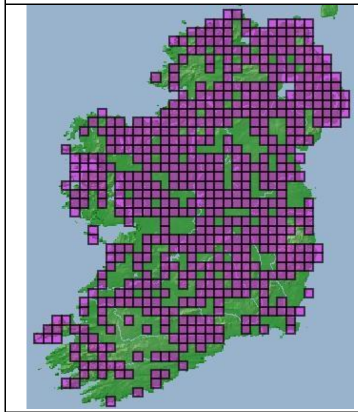
A4.1 Snails

<table>
<tr><td>Latin Name</td><td>Common name</td><td>Recommended authority</td></tr>
<tr><td>Aegopinella nitidula</td><td>Smooth Glass Snail</td><td>Draparnaud, 1805</td></tr>
<tr><td></td><td></td><td rowspan="2">Species found in samples from:
<table>
<tr><td>Turlough More</td><td>Fanore</td><td>Dale Head</td><td>High Folds</td><td>Holme Park Quarry</td></tr>
<tr><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td></tr>
</table>

ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Least concern (National Parks & Wildlife Service, 2016)

Habitat: The Smooth Glass Snail is very common in Britain and Ireland, and found as far south as Spain and as far north as Norway (Forsyth, Hutchinson & Reise, 2001). It is found in a wide variety of habitats including woods, hedges, gardens, rough grassland and waste ground (Cameron, 2003). Their diet is mostly made up of dead plant material, however there are indications that they may also eat other smaller snails (Forsyth, Hutchinson & Reise, 2001). This predatory behaviour can impact the distribution of Aegopinella pura and Vitrea crystallina (Forsyth, Hutchinson & Reise, 2001; Myzyk, 2014).</td></tr>
<tr><td>Irish distribution of Aegopinella nitidula (Biodiversity Maps, 2019a)</td><td>UK distribution of Aegopinella nitidula (NBN Atlas, 2019a)</td></tr>
</table>

Latin Name	Common name	Recommended authority
Aegopinella pura	Clear Glass Snail	Alder, 1830



Irish distribution of *Aegopinella pura* (Biodiversity Maps, 2019b)

UK distribution of *Aegopinella pura* (NBN Atlas, 2019b)

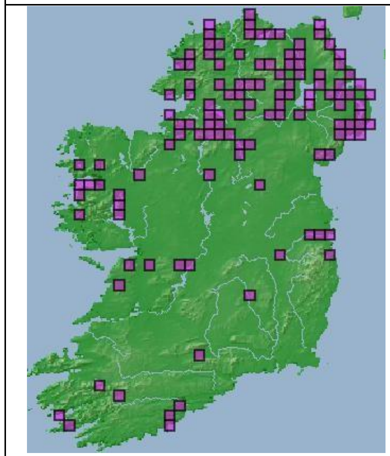
Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
x	x		x	x

ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

Habitat: The Clear Glass snail is common in woodland, leaf-litter and sometimes in hedges, and has an affinity to sites with coarse woody debris (Cameron, 2003; Kappa's, 2005). The geographical distribution for this species is limited to Europe, and is not found in the extreme north or south of the continent (NBN Atlas, 2019b).

Latin Name	Common name	Recommended authority
Balea sarsii		Pfeiffer, 1847



Irish distribution of *Balea sarsii* (Biodiversity Maps, 2019c)

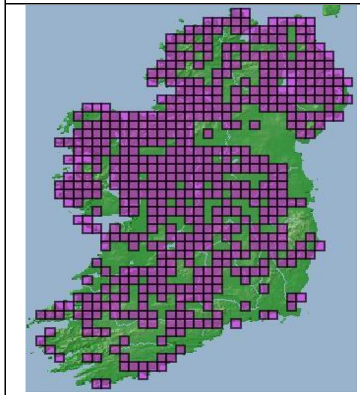
UK distribution of *Balea sarsii* (NBN Atlas, 2019c)

Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
		x		

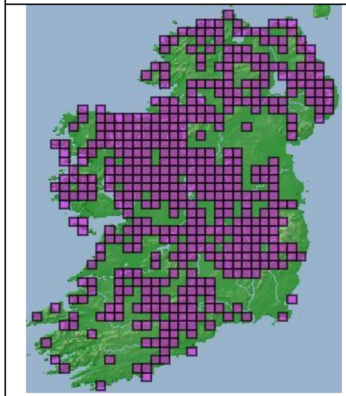
ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

Habitat: This species is rarely found on the ground, and is often found climbing limestone and lime mortared walls. It is tolerant of sea exposure and mainly eats lichens (Von Proschwitz, 2010). It is suggested to be declining in the Republic of Ireland, however, it is found as far south as Spain and as far north as Sweden (Von Proschwitz, 2010; National Parks & Wildlife Service, 2016).

<table>
<tr><td>Latin Name</td><td>Common name</td><td>Recommended authority</td></tr>
<tr><td>Carychium minimum</td><td>Short-Toothed Herald Snail</td><td>O. F. Müller, 1774</td></tr>
<tr><td>
Irish distribution of Carychium minimum (Biodiversity Maps, 2019d)</td><td>
UK distribution of Carychium minimum (NBN Atlas, 2019d)</td><td>Species found in samples from:
<table>
<tr><td>Turlough More</td><td>Fanore</td><td>Dale Head</td><td>High Folds</td><td>Holme Park Quarry</td></tr>
<tr><td></td><td>X</td><td>x</td><td>x</td><td>x</td></tr>
</table>

ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018).
Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

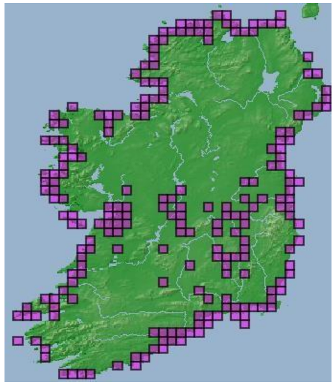
Habitat: Widespread in Britain and Ireland, and found in many areas of Europe including Spain at the most southern extent and Norway at the most northern extent (NBN Atlas, 2019d; Price, et al., 2018). Carychium minimum is found in wetlands and woodland, and has a preference for more moist soils (Cameron, 2003; Čejka & Hamerlik,2009)</td></tr>
</table>

<table>
<tr><td>Latin Name</td><td>Common name</td><td>Recommended authority</td></tr>
<tr><td>Carychium tridentatum</td><td>Long-toothed herald snail</td><td>Risso, 1826</td></tr>
<tr><td>
Irish distribution of Carychium tridentatum (Biodiversity Maps, 2019e)</td><td>
UK distribution of Carychium tridentatum (NBN Atlas, 2019e)</td><td>Species found in samples from:
<table>
<tr><td>Turlough More</td><td>Fanore</td><td>Dale Head</td><td>High Folds</td><td>Holme Park Quarry</td></tr>
<tr><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td></tr>
</table>

ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

Habitat: Carychium tridentatum is widespread in Britain and Ireland and found as far south as North Africa (Welter-Schultes, 2012). It is found in leaf-litter, woods, hedges and especially abundant in calcareous soils and can even be described as an obligatory calciphile (Morton, 1954; Cameron, 2003). It is found in particularly moist environments, can tolerate a marine environment and may become immobile if too dry (Morton, 1954; Ondina, Hermida, Outeiro & Mato, 2004).</td></tr>
</table>

Latin Name	Common name	Recommended authority
Cochlicella acuta	Pointed Snail	Muller, 1774



Irish distribution of *Cochlicella acuta* (Biodiversity Maps, 2019f)

UK distribution of *Cochlicella acuta* (NBN Atlas, 2019f)

Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
			x	

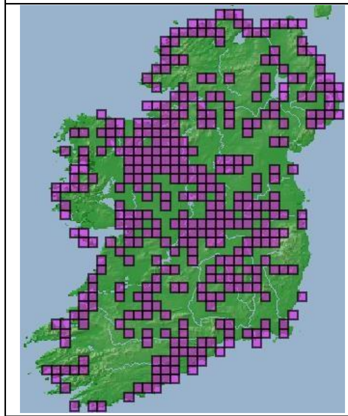
ICUN Conservation status: Least Concern

Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)

Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

Habitat: This species is found widely on the coasts of Britain and Ireland, is native to the Mediterranean and can be found as widely as Australia (Baker, Hawke & Vogelzang, 1991). It is often found on calcareous soils, but is also particularly abundant in sand dunes (Cameron, 2003).

Latin Name	Common name	Recommended authority
Cochlicopa cf. lubricella	Least Slippery Snail	Rossmässler, 1834



Irish distribution of *Cochlicopa cf. lubricella* (Biodiversity Maps, 2019g)

UK distribution of *Cochlicopa cf. lubricella* (NBN Atlas, 2019g)

Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
		x		

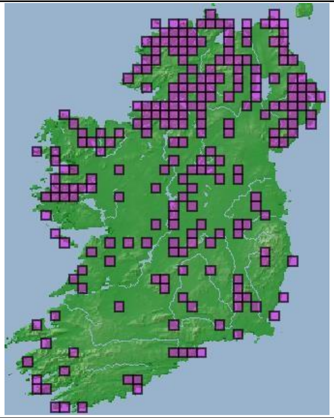
ICUN Conservation status: Least Concern

Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)

Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

Habitat: Widely found in Britain and Ireland, and also found in parts of eastern Europe (Welter-Schultes, 2012). *Cochlicopa cf. lubricella's* preferred habit is dry pastures in limestone areas and also sand dunes on the coast (Cameron, 2003).

Latin Name	Common name	Recommended authority
Columella aspera		Waldén, 1966



Irish distribution of *Columella aspera* (Biodiversity Maps, 2019h)

UK distribution of *Columella aspera* (NBN Atlas, 2019h)

Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
			x	

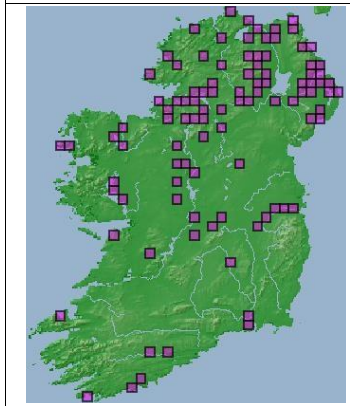
ICUN Conservation status: Least Concern

Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)

Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

Habitat: Found widely in Britain and Ireland and parts of eastern Europe (Cameron, 2003). Widespread and found commonly in oligotrophic sites including dry acidic woodland, but also tolerant of high levels of calcium and moisture (Johannessen & Solhøy, 2001; Cameron, 2003; Ondina, Hermida, Outeiro & Mato, 2004).

Latin Name	Common name	Recommended authority
Columella edentula	Toothless Chrysalis Snail	Draparnaud, 1805



Irish distribution of *Columella edentula* (Biodiversity Maps, 2019i)

UK distribution of *Columella edentula* (NBN Atlas, 2019i)

Species found in samples from:

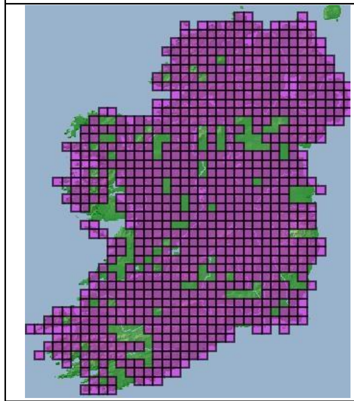
Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
		x	x	

ICUN Conservation status: Least Concern

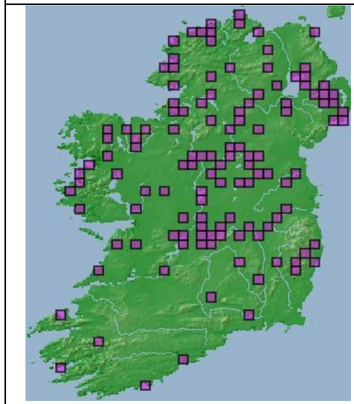
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)

Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

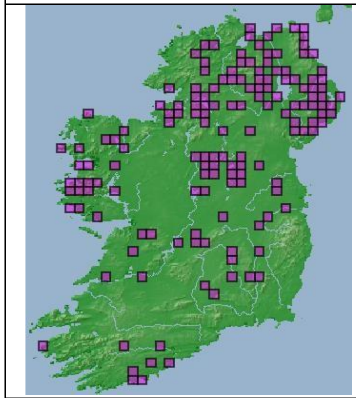
Habitat: This species is widespread throughout many habitats and normally found in eutrophic soils. *Columella edentula* is adapted to low humidity environments and frequently climbs vegetation such as ferns (Cameron, 2003; Książkiewicz, Kiaszewicz & Gotdyn, 2013). Occurs rarely in the Republic of Ireland, but is found widely in the UK and parts of Ukraine (Kappes, 2005; Welter-Schultes, 2012).

<table>
<tr><td>Latin Name</td><td>Common name</td><td>Recommended authority</td></tr>
<tr><td>Discus rotundatus</td><td>Rounded Snail</td><td>Müller, 1774</td></tr>
<tr><td></td><td></td><td rowspan="2">Species found in samples from:
<table><tr><td>Turlough More</td><td>Fanore</td><td>Dale Head</td><td>High Folds</td><td>Holme Park Quarry</td></tr><tr><td></td><td>x</td><td>x</td><td>x</td><td>x</td></tr></table>
ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

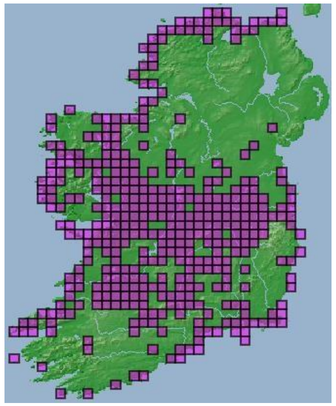
Habitat: This species is very common in both Britain and the Republic of Ireland. Discus rotundatus is found in parts of eastern Europe and as far south as Italy and Turkey (Kuznik-Kowalska, 1999). It is usually in woodlands and hedges and is recorded to prefer sites with coarse woody debris (Cameron, 2003; Kappes, 2005). This species can tolerate a wide pH range and has been known to cannibalise conspecific eggs (Kuznik-Kowalska, 1999).</td></tr>
<tr><td>Irish distribution of Discus rotundatus (Biodiversity Maps, 2019j)</td><td>UK distribution of Discus rotundatus (NBN Atlas, 2019j)</td></tr>
</table>

<table>
<tr><td>Latin Name</td><td>Common name</td><td>Recommended authority</td></tr>
<tr><td>Euconulus alderi</td><td></td><td>J. E. Gray, 1840</td></tr>
<tr><td></td><td></td><td rowspan="2">Species found in samples from:
<table><tr><td>Turlough More</td><td>Fanore</td><td>Dale Head</td><td>High Folds</td><td>Holme Park Quarry</td></tr><tr><td></td><td></td><td></td><td>x</td><td>x</td></tr></table>
ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

Habitat: Widespread in the UK but found more sparsely in the Republic of Ireland, this species can be found in other parts of the USA and Europe of a similar latitude (Nekola, 2003; NBN Atlas, 2019k). This species is commonly found in wetlands and has a preference for more humid habitats (Cameron, 2003).</td></tr>
<tr><td>Irish distribution of Euconulus alderi (Biodiversity Maps, 2019k)</td><td>UK distribution of Euconulus alderi (NBN Atlas, 2019k)</td></tr>
</table>

<table>
<tr><td>Latin Name</td><td>Common name</td><td>Recommended authority</td></tr>
<tr><td>Euconulus fulvus</td><td>Tawny Glass Snail</td><td>O. F. Müller, 1774</td></tr>
<tr><td></td><td></td><td rowspan="2">Species found in samples from:
<table><tr><td>Turlough More</td><td>Fanore</td><td>Dale Head</td><td>High Folds</td><td>Holme Park Quarry</td></tr><tr><td>x</td><td></td><td></td><td>x</td><td></td></tr></table>
ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

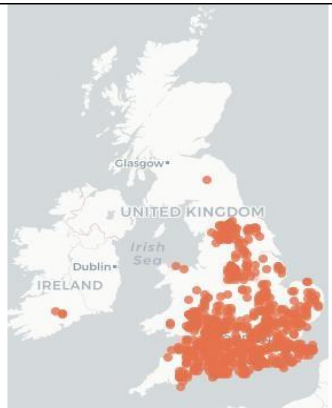
Habitat: Euconulus fulvus is widespread in the UK but less common in the Republic of Ireland, and also found in parts of eastern Europe (NBN Atlas, 2019l). It is found in leaf-litter and under logs in both coniferous and deciduous forests in Britain and Ireland (Cameron, 2003, Welter-Schultes, 2012). This species is tolerant of non-calcareous soils and does not increase in number past a pH of 6.5 as other snails might (Valovirta, 1968; Welter-Schultes, 2012)</td></tr>
<tr><td>Irish distribution of Euconulus fulvus (Biodiversity Maps, 2019l)</td><td>UK distribution of Euconulus fulvus (NBN Atlas, 2019l)</td></tr>
</table>

<table>
<tr><td>Latin Name</td><td>Common name</td><td>Recommended authority</td></tr>
<tr><td>Helicella itala</td><td>Heath Snail</td><td>Linnaeus, 1758</td></tr>
<tr><td></td><td></td><td rowspan="2">Species found in samples from:
<table><tr><td>Turlough More</td><td>Fanore</td><td>Dale Head</td><td>High Folds</td><td>Holme Park Quarry</td></tr><tr><td></td><td>x</td><td></td><td></td><td></td></tr></table>
ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened, Priority Species (Northern Ireland) (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Vulnerable (National Parks & Wildlife Service, 2016)

Habitat: Widespread but retreating from coastal regions. Commonly found in short dry calcareous grassland and dunes (Cameron, 2003). Thought to be declining and found primarily in the central limestone plains in the Republic of Ireland.</td></tr>
<tr><td>Irish distribution of Helicella itala (Biodiversity Maps, 2019m)</td><td>UK distribution of Helicella itala (NBN Atlas, 2019m)</td></tr>
</table>

Latin Name	Common name	Recommended authority
Helicigona lapicida	Lapidary Snail	Linnaeus, 1758

Irish distribution of *Helicigona lapicida* (Biodiversity Maps, 2019n)



UK distribution of *Helicigona lapicida* (NBN Atlas, 2019n)

Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
				x

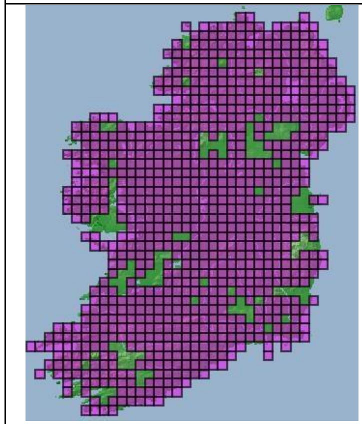
ICUN Conservation status: Least Concern

Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)

Republic of Ireland Conservation status: Regionally extinct (National Parks & Wildlife Service, 2016)

Habitat: Widespread in England and found commonly in calcareous soils, limestone rocks and woodlands (Cameron, 2003). Specimens from the Republic of Ireland have not been found in recent years (National Parks & Wildlife Service, 2016). This species typically grazes on lichens and has a high preference for humid habitats, such that it is rarely active during dry periods (Baur, Baur, & Fröberg, 1994).

Latin Name	Common name	Recommended authority
Lauria cylindracea	Common Chrysalis Snail	Da Costa, 1778



Irish distribution of *Lauria cylindracea* (Biodiversity Maps, 2019o)

UK distribution of *Lauria cylindracea* (NBN Atlas, 2019o)

Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
x	x	x	x	x

ICUN Conservation status: Least Concern

Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)

Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

Habitat: Widespread in Britain and Ireland. Found in woodland damp grassland, walls, hedges and exposed rocks (Cameron, 2003). This species is found as far south as the Mediterranean and capable of surviving long periods of desiccation (Arad, Goldenberg & Heller, 1998).

Latin Name	Common name	Recommended authority
Lucilla singleyana	*Lucilla singleyana*	Pilsbry, 1889

Irish distribution of *Lucilla singleyana* (Biodiversity Maps, 2019p)

UK distribution of *Lucilla singleyana* (NBN Atlas, 2019p)

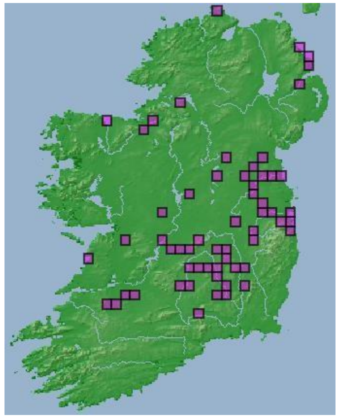
Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
		X		X

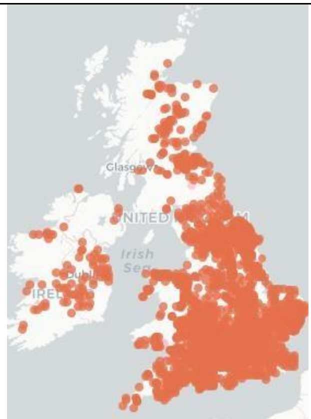
ICUN Conservation status: Not Evaluated
Great Britain Conservation status: Not Evaluated
Republic of Ireland Conservation status: Not present (National Parks & Wildlife Service, 2016)

Habitat: A relatively recent introduction to the UK, known to be mainly subterranean (Cameron, 2003). This species is largely confined to cooler climates, it has been identified as being found more frequently at high elevations in Pennsylvania in the United States where it has been identified as being susceptible to climate change (Pearce & Paustian, 2013).

Latin Name	Common name	Recommended authority
Merdigera obscura	Lesser Bulin	O. F. Müller, 1774



Irish distribution of *Merdigera obscura* (Biodiversity Maps, 2019q)



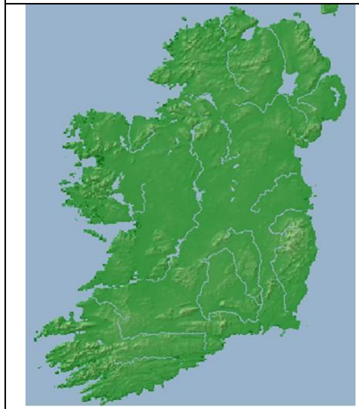
UK distribution of *Merdigera obscura* (NBN Atlas, 2019q)

Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
			x	

ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Endangered (National Parks & Wildlife Service, 2016)

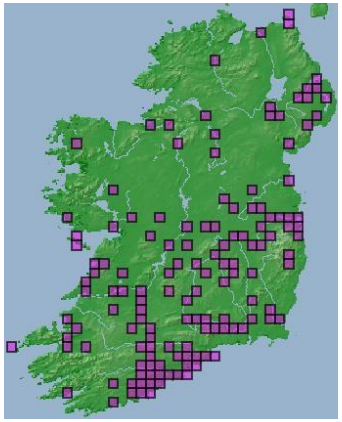
Habitat: Common in the UK, in woods, hedges and calcareous soils (Cameron, 2003). In severe decline in the Republic of Ireland and associated with calcareous escarpments and calcareous woodlands (National Parks & Wildlife Service, 2016). This species can be found in Mediterranean climates, where it has an affinity toward more humid (Pilāte, Cibuļskis & Jakubāne 2014).

<table>
<tr><td>Latin Name</td><td>Common name</td><td>Recommended authority</td></tr>
<tr><td>Oxychilus alliarius</td><td>Garlic Snail</td><td>J. S. Miller, 1822</td></tr>
<tr><td></td><td></td><td rowspan="2">Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
		x		x

ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Not present (National Parks & Wildlife Service, 2016)

Habitat: Oxychilus species are common in rocky sheltered habitats such as scree (Cameron, 2003). This species is widespread in Western Europe, occurring as far south as West France to as far north as Southern Norway (Horácková & Juricková, 2009).</td></tr>
<tr><td>Irish distribution of Oxychilus alliarius (Biodiversity Maps, 2019r)</td><td>UK distribution of Oxychilus alliarius (NBN Atlas, 2019r)</td></tr>
</table>

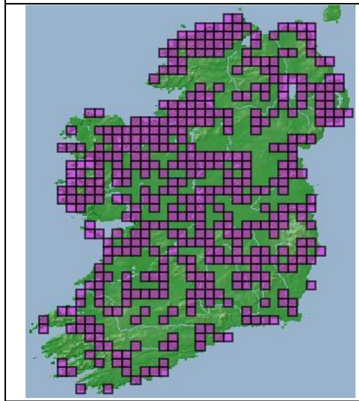
<table>
<tr><td>Latin Name</td><td>Common name</td><td>Recommended authority</td></tr>
<tr><td>Oxychilus draparnaudi</td><td>Draparnaud's Glass Snail</td><td>H. Beck, 1837</td></tr>
<tr><td></td><td></td><td rowspan="2">Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
	x			x

ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

Habitat: Oxychilus species are common in rocky sheltered habitats such as scree (Cameron, 2003). This species is found widely in the Mediterranean, however human activity has spread it to parts of South Africa (Van Bruggen, 1964)</td></tr>
<tr><td>Irish distribution of Oxychilus draparnaudi (Biodiversity Maps, 2019s)</td><td>UK distribution of Oxychilus draparnaudi (NBN Atlas, 2019s)</td></tr>
</table>

Latin Name	Common name	Recommended authority
Punctum pygmaeum	Dwarf Snail	Draparnaud, 1801



Irish distribution of *Punctum pygmaeum* (Biodiversity Maps, 2019t)

UK distribution of *Punctum pygmaeum* (NBN Atlas, 2019t)

Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
x	x	x	x	X

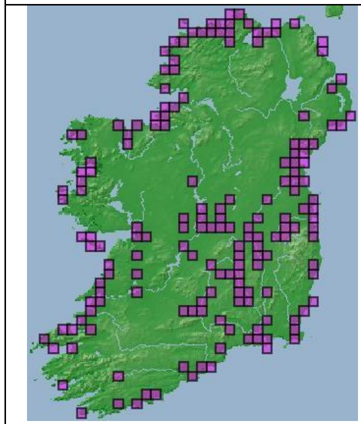
ICUN Conservation status: Least Concern

Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)

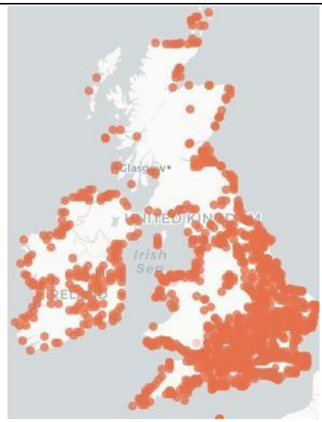
Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

Habitat: Common and widespread in Britain and Ireland, usually in leaf-litter (Cameron, 2003). *Punctum pygmaeum* is found as far south as the West of Spain, but may also be found in northern Norway (Andersen & Halvorsen, 1984; Ondina, Hermida, Outeiro & Mato, 2004).

Latin Name	Common name	Recommended authority
Pupilla muscorum	Moss Chrysalis Snail	Linnaeus, 1758



Irish distribution of *Pupilla muscorum* (Biodiversity Maps, 2019u)



UK distribution *Pupilla muscorum* (NBN Atlas, 2019u)

Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
		x	x	

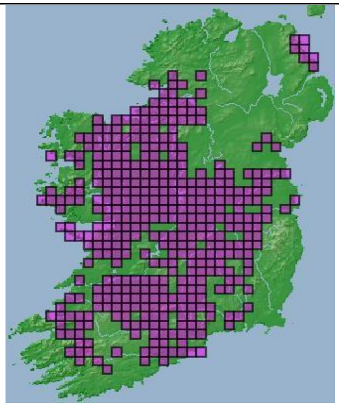
ICUN Conservation status: Least Concern

Great Britain Conservation status: Taxa which are neither threatened nor near threatened, Priority Species (Northern Ireland) (Joint Nature Conservation Committee, 2018)

Republic of Ireland Conservation status: Endangered (National Parks & Wildlife Service, 2016)

Habitat: Found on dry calcareous grassland and dunes in sunny positions in the whole of Britain and Ireland, but declining (Cameron, 2003). This species is found across Europe and as far north as northern Norway (Andersen & Halvorsen, 1984; Welter-Schultes, 2012).

Latin Name	Common name	Recommended authority
Pyramidula pusilla	Rock Snail	Vallot, 1801



Irish distribution of *Pyramidula pusilla* (Biodiversity Maps, 2019v)

UK distribution *Pyramidula pusilla* (NBN Atlas, 2019v)

Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
x	x	x		

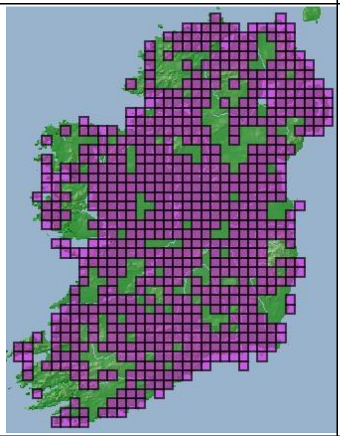
ICUN Conservation status: Least Concern

Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)

Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

Habitat: largely restricted to dry, exposed or part shaded limestone (Cameron, 2003). This species has been identified widely in Europe and the entire Mediterranean area, however there is evidence to suggest that in Britain *Pyramidula pusilla* is replaced by a conspecific subspecies (Gittenberger & Bank, 1996).

Latin Name	Common name	Recommended authority
Trochulus hispidus	Hairy Snail	Linnaeus, 1758



Irish distribution of *Trochulus hispidus* (Biodiversity Maps, 2019w)

UK distribution *Trochulus hispidus* (NBN Atlas, 2019w)

Species found in samples from:

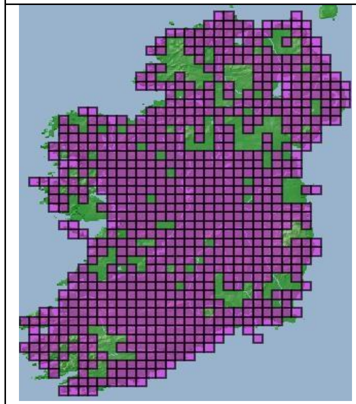
Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
		x	x	

ICUN Conservation status: Least Concern

Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)

Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

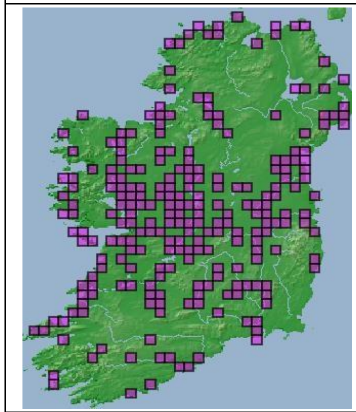
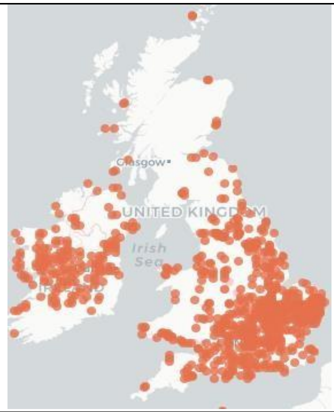
Habitat: common and widespread in woods, wetlands, hedges, rough ground and calcareous grassland (Cameron, 2003). This species is found in the Mediterranian and arctic circle and most areas of Europe between (Prćków, Drvotová, Juřičková & Kuźnik-Kowalska, 2013).

Latin Name	Common name	Recommended authority
Trochulus striolatus	Strawberry Snail	C. Pfeiffer, 1828
		Species found in samples from:
Irish distribution of *Trochulus striolatus* (Biodiversity Maps, 2019x)	UK distribution *Trochulus striolatus* (NBN Atlas, 2019x)	

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
	x			

ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

Habitat: Encountered in wet shady areas in many areas of Britain and Ireland (Cameron, 2003). This species is found widely in Western Europe, however has a preference for more humid environments during the summer (Proców, 2009).

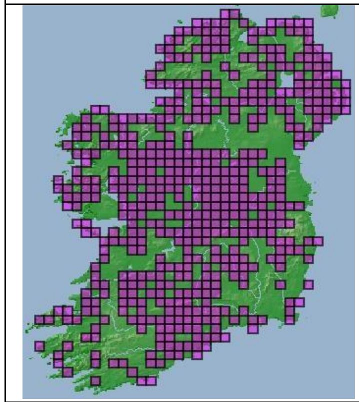
Latin Name	Common name	Recommended authority
Vallonia pulchella	Smooth Grass Snail	O. F. Müller, 1774
		Species found in samples from:
Irish distribution of *Vallonia pulchella* (Biodiversity Maps, 2019y)	UK distribution *Vallonia pulchella* (NBN Atlas, 2019y)	

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
			x	

ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened, Priority Species (Northern Ireland) (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Vulnerable (National Parks & Wildlife Service, 2016)

Habitat: Found in open damp habitats including wetlands and ditches (Cameron, 2003). In the Republic of Ireland this species is found mainly in pasture and on the floodplains of lakes and rivers inland (National Parks & Wildlife Service, 2016). This species has a wide distribution from North Scandinavia to the Middle East, in warmer countries it is found to be more heat tolerant than others of its Genus (Welter-Schultes, 2012).

Latin Name	Common name	Recommended authority
Vitrea contracta	Milky Crystal Snail	Westerlund, 1871



Irish distribution of *Vitrea contracta* (Biodiversity Maps, 2019z)

UK distribution *Vitrea contracta* (NBN Atlas, 2019z)

Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
x	x	x	x	x

ICUN Conservation status: Least Concern

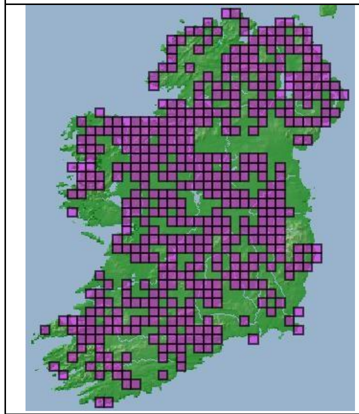
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)

Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

Habitat: Common and widespread in Britain and Ireland, preferring drier calcareous habitats (Cameron, 2003).

This species is found in Europe and neighbouring parts of Asia and North Arica (Georgiev & Dedov, 2014).

Latin Name	Common name	Recommended authority
Vitrea crystallina	Crystal Snail	O. F. Müller, 1774



Irish distribution of *Vitrea crystallina* (Biodiversity Maps, 2019aa)

UK distribution *Vitrea crystallina* (NBN Atlas, 2019aa)

Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
x	x	x	x	x

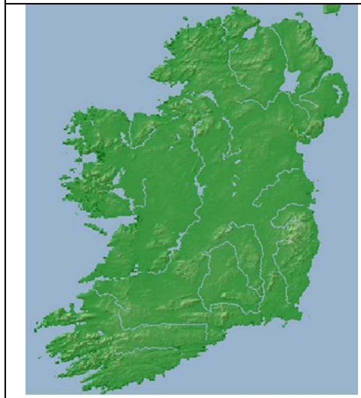
ICUN Conservation status: Least Concern

Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)

Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

Habitat: Common in many habitats in both Britain and the Republic of Ireland, often missing in drier habitats (Cameron, 2003). This species is found in most of Europe, but rarely found in the South of the continent (Welter-Schultes, 2012)

Latin Name	Common name	Recommended authority
Vitrea subrimata		Reinhardt, 1871



Irish distribution of *Vitrea subrimata* (Biodiversity Maps, 2019ab)

UK distribution *Vitrea subrimata* (NBN Atlas, 2019ab)

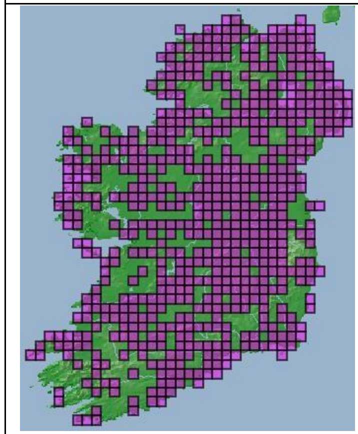
Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
		x	x	x

ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened, Nationally Scarce - Occurring in 16-100 hectares in Great Britain (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Not present (National Parks & Wildlife Service, 2016)

Habitat: The distribution in Britain and Ireland for *Vitrea subrimata* is restricted to calcareous habitats in the north of England (Cameron, 2003). This species is widely found in Europe and North Africa, where it is found in humid habitats (Welter-Schultes, 2012)

Latin Name	Common name	Recommended authority
Vitrina pellucida	Pellucid Glass Snail	O. F. Müller, 1774



Irish distribution of *Vitrina pellucida* (Biodiversity Maps, 2019ac)

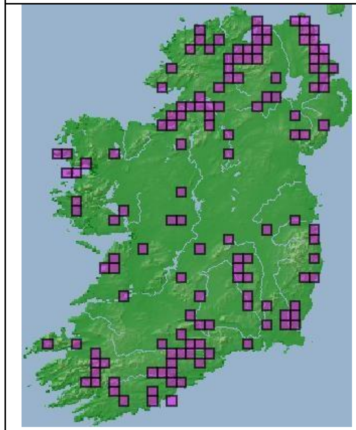
UK distribution *Vitrina pellucida* (NBN Atlas, 2019ac)

Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
		x	x	

ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Least Concern (National Parks & Wildlife Service, 2016)

Habitat: Common and widespread in Britain and Ireland, in both woodland and open habitats, with a preference for wetter shady places (Cameron, 2003; Pilsbry & Tryon, 2009). This species is widely distributed from Central Asia to the Arctic Circle (Welter-Schultes, 2012).

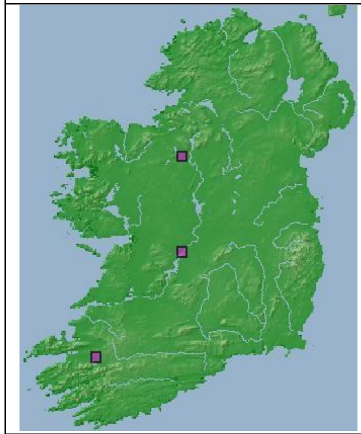
<table>
<tr><td>Latin Name</td><td>Common name</td><td>Recommended authority</td></tr>
<tr><td>Zenobiella subrufescens</td><td>Brown Snail</td><td>J. S. Miller, 1822</td></tr>
<tr><td></td><td>
</td><td rowspan="2">Species found in samples from:

Turlough More	Fanore	Dale Head	High Folds	Holme Park Quarry
		x	x	

ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened, Priority Species (Northern Ireland) (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Vulnerable (National Parks & Wildlife Service, 2016)

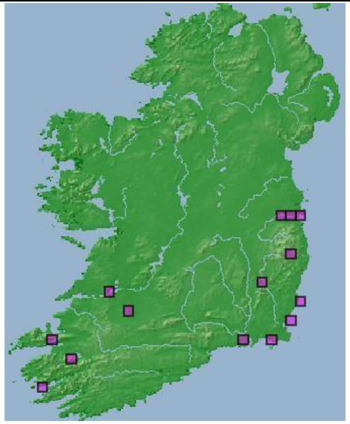
Habitat: Widespread in both Britain and the Republic of Ireland. Found in old woodland and climbs vegetation (Cameron, 2003). This species is found in parts of Spain and Britain is the most northerly distribution (Welter-Schultes, 2012).</td></tr>
<tr><td>Irish distribution of Zenobiella subrufescens (Biodiversity Maps, 2019ad)</td><td>UK distribution Zenobiella subrufescens (NBN Atlas, 2019ad)</td></tr>
</table>

A4.2 Woodlice

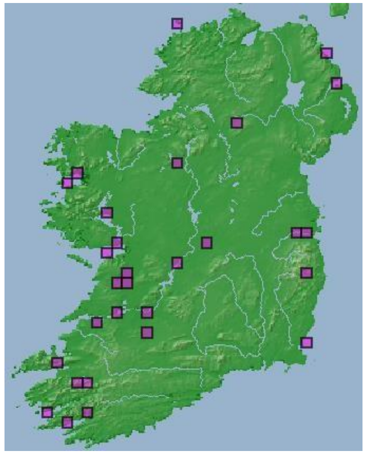
<table>
<tr><td>Latin Name</td><td>Common name</td><td>Recommended authority</td></tr>
<tr><td>Androniscus dentiger</td><td>Rosy Woodlouse</td><td>Verhoeff, 1908</td></tr>
<tr><td></td><td></td><td rowspan="2">Species found in samples from:
<table>
<tr><td>Turlough More</td><td>Fanore</td><td>Dale Head</td><td>High Folds</td><td>Holme Park Quarry</td></tr>
<tr><td></td><td></td><td></td><td>x</td><td></td></tr>
</table>

ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Not yet allocated

Habitat: This species has been considered to be synanthropic because of the common occurrence in human environments; however it also occurs naturally in caves, screes, maritime cliff faces and shorelines (Harding, 1985).</td></tr>
<tr><td>Irish distribution of Androniscus dentiger (Biodiversity Maps, 2019ae)</td><td>UK distribution Androniscus dentiger (NBN Atlas, 2019ae)</td></tr>
</table>

<table>
<tr><td>Latin Name</td><td>Common name</td><td>Recommended authority</td></tr>
<tr><td>Armadillidium vulgare</td><td>Common Pill Woodlouse</td><td>Latreille, 1804</td></tr>
<tr><td></td><td></td><td rowspan="2">Species found in samples from:
<table>
<tr><td>Turlough More</td><td>Fanore</td><td>Dale Head</td><td>High Folds</td><td>Holme Park Quarry</td></tr>
<tr><td></td><td></td><td>x</td><td>x</td><td>x</td></tr>
</table>

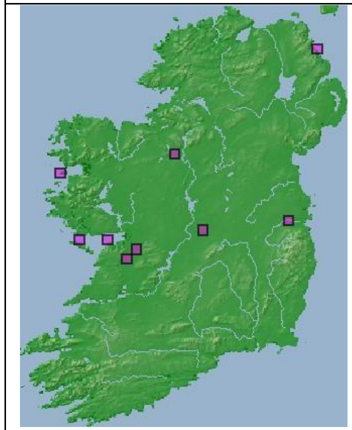
ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Not yet allocated

Habitat: Common in the southeast of Britain and increasingly found in coastal or synanthropic habitats in the north and west. Preferred habitats include calcareous grassland in Yorkshire and The Burren (Harding, 1985).</td></tr>
<tr><td>Irish distribution of Armadillidium vulgare (Biodiversity Maps, 2019af)</td><td>UK distribution Armadillidium vulgare (NBN Atlas, 2019af)</td></tr>
<tr><td>Latin Name</td><td>Common name</td><td>Recommended authority</td></tr>
<tr><td>Oniscus asellus</td><td>Common Shiny Woodlouse</td><td>Linnaeus, 1758</td></tr>
<tr><td></td><td></td><td rowspan="2">Species found in samples from:
<table>
<tr><td>Turlough More</td><td>Fanore</td><td>Dale Head</td><td>High Folds</td><td>Holme Park Quarry</td></tr>
<tr><td>x</td><td></td><td>x</td><td>x</td><td>x</td></tr>
</table>

ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Not yet allocated

Habitat: The most widely distributed woodlouse species in Britain and Ireland. Found commonly and latched to the underside of stones and dead wood, possibly giving rise to the name “woodlouse”. Despite a strong preference for calcareous conditions it is tolerant of more acidic conditions, but does not tolerate dry conditions well (Harding, 1985).</td></tr>
<tr><td>Irish distribution of Oniscus asellus (Biodiversity Maps, 2019ag)</td><td>UK distribution Oniscus asellus (NBN Atlas, 2019ag)</td></tr>
</table>

<table>
<tr><td>Latin Name</td><td>Common name</td><td>Recommended authority</td></tr>
<tr><td>Porcellio scaber</td><td>Common rough woodlouse</td><td>Latreille, 1804</td></tr>
<tr><td></td><td></td><td rowspan="2">Species found in samples from:
<table>
<tr><td>Turlough More</td><td>Fanore</td><td>Dale Head</td><td>High Folds</td><td>Holme Park Quarry</td></tr>
<tr><td></td><td></td><td>x</td><td>x</td><td>x</td></tr>
</table>
ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Not yet allocated
Habitat: The second most widely distributed woodlouse in Britain and Ireland with very similar habitat preference as Oniscus asellus. This species has the subjective impression of being able to tolerate dryer conditions than that of O. asellus and the tendency to live up trees during summer (Harding, 1985). </td></tr>
<tr><td>Irish distribution of Porcellio scaber (Biodiversity Maps, 2019ah)</td><td>UK distribution Porcellio scaber (NBN Atlas, 2019ah)</td></tr>
</table>

<table>
<tr><td>Latin Name</td><td>Common name</td><td>Recommended authority</td></tr>
<tr><td>Trichoniscus pusillus</td><td>common pygmy woodlouse</td><td>Brandt, 1833</td></tr>
<tr><td></td><td></td><td rowspan="2">Species found in samples from:
<table>
<tr><td>Turlough More</td><td>Fanore</td><td>Dale Head</td><td>High Folds</td><td>Holme Park Quarry</td></tr>
<tr><td></td><td></td><td>x</td><td>x</td><td></td></tr>
</table>
ICUN Conservation status: Least Concern
Great Britain Conservation status: Taxa which are neither threatened nor near threatened (Joint Nature Conservation Committee, 2018)
Republic of Ireland Conservation status: Not yet allocated
Habitat: Ubiquitous throughout Britain and Ireland and found equally in calcareous and non-calcareous habitats (Harding, 1985). This species is found deeply bedded in leaf litter, as it is highly susceptible to desiccation (Sutton, 1968). </td></tr>
<tr><td>Irish distribution of Trichoniscus pusillus (Biodiversity Maps, 2019ai)</td><td>UK distribution Trichoniscus pusillus (NBN Atlas, 2019ai)</td></tr>
</table>

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